DGR Deutsche Gesellschaft für Robotik

Proceedings

DGR Days 2021

October, 06 – 08, online, hosted in Karlsruhe

Program Chairs

Tamim Asfour, Karlsruhe Institute of Technology
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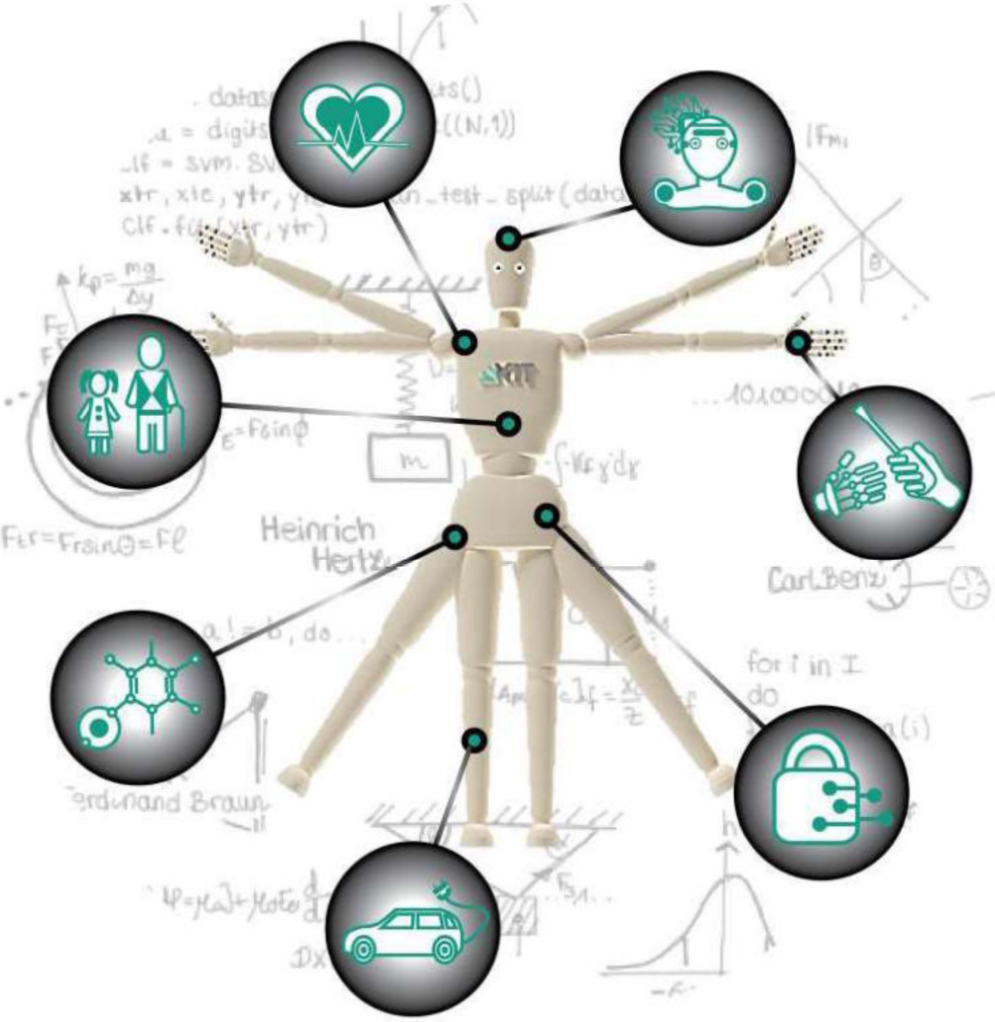
Timetable



Wednesday, October 6

09:50 - 10:00	**Welcome**	
10:00 - 18:00	**Keynotes**	
10:00	Yoshihiko Nakamura Personal Digital-Twin and Data Science	
11:00	Manuela Veloso From AI in Robotics to AI in Finance: Examples and Discussion	
12:00	Danica Kragic Robots: Perceiving, Interacting, Collaborating	
13:00 - 14:00	**Break**	
14:00	Sami Haddadin Breaking the Wall to Collective Learning: How AI and Networked Robotics can Kickstart Machine Evolution	
15:00 - 16:00	**Break**	
16:00	Wolfram Burgard Probabilistic and Deep Learning Approaches for Robot Navigation and Autonomous Driving	
17:00	Caroline Uhler *Gaul Lecture*: Causality and Autoencoders in the Light of Drug Repurposing for COVID-19	

Thursday, October 7

10:00 - 12:00 Keynotes

10:00 Cyrill Stachniss
Robotics and Phenotyping for Sustainable Crop Production

11:00 Daniel Dahlmeier
Developing AI for B2B Applications

12:00 - 13:30 DGR Days Session: Walking & Wearable Robotics

12:00 Bio-Inspired Compliant Motion Control in the Context of Bipedal Locomotion
P. Vonwirth, K. Berns

12:12 Effective Viscous Damping for Legged Robots
A. Mo, F. Izzi, D. Haeufle, A. Badri-Spröwitz

12:24 Questions around the Catapult Mechanism in Human Legged Locomotion
B. Kiss, A. Buchmann, D. Renjewski, A. Badri-Spröwitz

12:36 Learning of Walking Gait Controllers for Magnetic Soft Millirobots
S. Özgün Demir, U. Culha, S. Trimpe, M. Sitti

12:48 Rigid, Soft, Passive and Active: a Hybrid Occupational Exoskeleton
Francesco Missiroli, Nicola Lotti, Enrica Tricomi, Casimir Bokranz, Ryan Alicea and Lorenzo Masia

13:00 Underactuated Soft Hip Exosuit Based on Adaptive Oscillators
E. Tricomi, N. Lotti, F. Missiroli, X. Zhang, L. Masia

13:12 The Benefit of Muscle-Actuated Motion in Optimization & Learning
I. Wochner, S. Schmitt

13:30 - 14:00 Break

14:00 - 15:30 DGR Days Session: Robot Learning

14:00 Extracting Strong Policies for Robotics Tasks from Zero-Order Trajectory Optimizers
S. Blaes, C. Pinneri, G. Martius

14:12 Specializing Versatile Skill Libraries using Local Mixture of Experts
M. Onur Celik, D. Zhou, G. Li, P. Becker, G. Neumann

14:24 Combining Manipulation Primitive Nets and Policy Gradient Methods for Learning Robotic Assembly Tasks
M. Braun, S. Wrede

Thursday, October 7

	DGR Days Session: Robot Learning
14:36	Robot Dynamics Learning with Action Conditional Recurrent Kalman Networks *V. Shaj, P. Becker, G. Neumann*
14:48	Seamless Sequencing of Skills via Differentiable Optimization *N. Jaquier, J. Starke, Y. Zhou, T. Asfour*
15:00	Learning Control Policies from Optimal Trajectories *C. Zelch, J. Peters, O. von Stryk*
15:30 - 16:00	**Break**
16:00 - 17:30	**Keynotes**
16:00	Hans-Jörg Fischer Legal Aspects of (General) AI The Electronic Person as Legal Consequence of the Development of General AI in the Future
16:45	Sabine Roeser Moral Emotions and the Promises and Risks of Artificial Intelligence

Friday, October 8

10:00 - 12:00 Keynotes

10:00 Oliver Brock
Machine Learning is Not Intelligence
What's Missing? And How We Might Create a Science of Intelligence

11:00 Khanlian Chung
xAI – Is This the Future of AI-Software Testing?

12:00 - 13:30 DGR Days Session: Learning for Grasping & Manipulation

12:00 Residual Feedback Learning for Contact-Rich Manipulation Tasks with Uncertainty
A. Ranjbar, N. Anh Vien, H. Ziesche, J. Boedecker, G. Neumann

12:12 Learning and Teaching Multimodal Neural Policies for Dexterous Manipulation
P. Ruppel, N. Hendrich, J. Zhang

12:24 Robot Hand Dexterous Manipulation by Teleoperation with Adaptive Force Control
C. Zeng, J. Zhang

12:36 Learning Robust Mobile Manipulation for Household Tasks
S. Jauhri, J. Peters, G. Chalvatzaki

12:48 Achieving Robustness in a Drawer Manipulation Task by using High-level Feedback instead of Planning
M. Baum, O. Brock

13:00 A Dataset for Learning Bimanual Task Models from Human Observation
F. Krebs, A. Meixner, I. Patzer, T. Asfour

13:12 EMG-driven Machine Learning Control of a Soft Glove for Grasping Assistance and Rehabilitation
M. Sierotowicz, N. Lotti, F. Missiroli, R. Alicea, M. Xiloyannis, C. Castellini, L. Masia

13:30 - 14:00 Break

Friday, October 8

14:00 - 15:30 DGR Days Session: Perception

14:00 Interconnected Recursive Filters in Artificial and Biological Vision
A. Battaje, O. Brock

14:12 Distributed Semantic Mapping for Heterogeneous Robotic Teams
Y. Fanger, T. Bodenmüller, R. Triebel

14:24 A Dexterous Hand-Arm Teleoperation System based on Hand Pose Estimation and Active Vision
S. Li, N. Hendrich, J. Zhang

14:36 Multimodal Perception for Robotic Pouring
H. Liang, N. Hendrich, J. Zhang

14:48 Physically Plausible Tracking & Reconstruction of Dynamic Objects
M. Strecke and J. Stueckler

15:00 Detecting Robotic Failures Using Visual Anomaly Detection
S. Thoduka, J. Gall, P. G. Plöger

15:12 Skill Generalisation and Experience Acquisition for Predicting and Avoiding Execution Failures
A. Mitrevski, P. G. Plöger, G. Lakemeyer

15:30 - 16:00 Break

16:00 - 17:30 DGR Days Session: Human-Robot-Interaction & Production

16:00 Improving HRI Through Robot Architecture Transparency
L. Hindemith, A.-L. Vollmer, B. Wrede

16:12 Improving Safety in Human-Robot Collaboration by using Brain-Computer Interface Technology
J. Lyu, A. Maye, J. Zhang, N. Hendrich, A. K. Engel

16:24 Flexibility in Human-Robot Teams
D. Riedelbauch

16:36 Towards Active Visual SLAM
E. Bonetto, A. Ahmad

16:48 Smart Interaction System for Autonomous Bus in Pedestrian Zone
Q. Hamza Jan, K. Berns

17:00 On the Principle of Transference & its Impact on Robotic Innovation
B. Bongardt

17:12 Sustainable Production enabled by remanufacturing
C. Hofmann, J.-P. Kaiser, N. Eschner

Bio-Inspired Compliant Motion Control
in the Context of Bipedal Locomotion

Patrick Vonwirth[1] and Karsten Berns[2]

Abstract— **Although being researched for decades, artificial, natural locomotion still has to be treated as an unsolved problem. Mathematical robot control strategies and natural walking models have been developed mostly aside each other. This work aims for bringing both these worlds closer together by combining known control algorithms with a bio-inspired compliant actuation concept.**

Preferred typ of presentation: Oral

I. Motivation and Problem Definition

Biological locomotion studies offer a deep insight into human-like gait. Joint motions, torques, power emittance or absorption and individual control purposes during the gait phases have been discovered. Simplified mechanical walking models, mostly based on the so-called SLIP (Spring Loaded Inverted Pendulum) model have been introduced to describe the natural, human gait.

On the other hand, a lot of different robot control concepts have been developed unrelated to each other and to these natural observations. However, all these approaches can be partitioned into two main classes: Mathematical and Biological ones. The focus of biological approaches lies in the similarity to nature, whereas mathematical concepts mainly focus on stability, efficiency or other control goals.

Unfortunately, the need for compliant motion when interacting with an unknown environment stays in strong contrast against classical control strategies. Consequently, a new actuation concept is needed that is capable of doing uncertain, compliant motion control while keeping the ability to execute existing, well-known and proven higher-level control tasks.

II. Related Work

Based on the human body, the *Compliant Robotic Leg* CARL has been developed [1]. It is driven only by electrical, series elastic actuators [2] that imitate natural muscles and by construction offer the required system compliance. Equivalent to a natural human body, CARL is equipped with more actuators than joints to control including actuators that span over and hence operate on two joints. Basic studies on the actuator coordination [3] and mounting [4] offered new insights and reasoning about the sense behind the natural construction of a human leg.

[1]Patrick Vonwirth is a 3rd year PhD student from the Robotics Research Lab, Department of Computer Science, University of Kaiserslautern, Kaiserslautern, Germany vonwirth@cs.uni-kl.de

[2]Karsten Berns (as supervisor) is the head of the Robotics Research Lab, Department of Computer Science, University of Kaiserslautern, Kaiserslautern, Germany berns@cs.uni-kl.de

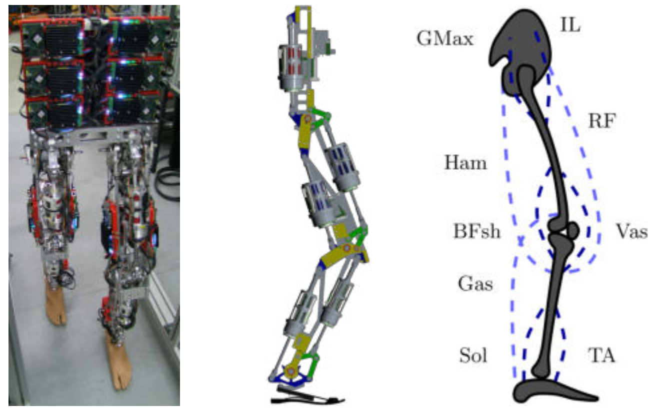


Fig. 1. The biped CARL, its leg's CAD-model and natural counterpart

III. Own Approach and Contribution

Inspired by the naturally observed SLIP-models, the *Bio-Inspired Compliant Motion Control* approach is based on a simple, robot abstraction model [5]. This model is especially designed to bridge the gap between the well-known mathematical control algorithms and the underlying bio-inspired, natural actuation system of CARL. Kinematic-based specialized algorithms, e.g. inverse kinematics in singular position [6], are used to operate the robot in natural limb configurations.

Further control concepts are about to be tested on CARL and integrated into the overall abstraction model control.

References

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Effective Viscous Damping for Legged Robots

An Mo[1], Fabio Izzi[1,2], Daniel F. B. Haeufle[2] and Alexander Badri-Spröwitz[1]

Abstract— **Animal observation and muscle models suggest that damping is beneficial for legged locomotion. Legged robots implement virtual damping at the controller level, while low-level mechanical damping is often overlooked despite its potential advantages. We aim to understand how mechanical damping can be exploited in legged robots for more robust behavior. By numerical simulation and hardware experiments with a 2-segment leg, we found a) adjustable, viscous damping is desired; b) hydraulic dampers are more effective than pneumatic dampers; c) adjustable dampers exhibit complex mechanic response when embedded into real legged systems.**

Preferred type of presentation: Poster

I. Motivation and Problem Definition

Intrinsic muscle damping likely plays an essential role in legged animal locomotion, providing benefits such as instantaneous response, producing adaptive joint torque, converting the system's energy, and rejecting unexpected perturbations [1, 2]. We want to understand how mechanical damping can be exploited in legged robots for more robust behavior.

II. Related Work

Legged robots commonly implement virtual damping at controller-level [3]. Virtual damping requires high-frequency control and sensing loops, precise sensors to identify loading conditions, and high-power actuators mechanically and electrically capable of producing negative power peaks.

In comparison, a mechanical damper can act instantaneously without the need for sensors or controllers. When coupled to the leg actuator in parallel, dampers can also share impact loads, which is ubiquitous in legged locomotion.

However, only a few implementations of mechanical damped systems exist in legged robots [4]. The requirements for mechanical dampers are not yet defined, and it remains unknown how the expected benefits from mechanical damping transfer into practice.

III. Own Approach and Contribution

We test our hypothesis with numerical simulations and hardware experiments, on a 2-segment leg with passive spring and damper parallel connected to the knee joint, in a simplified drop scenario [5].

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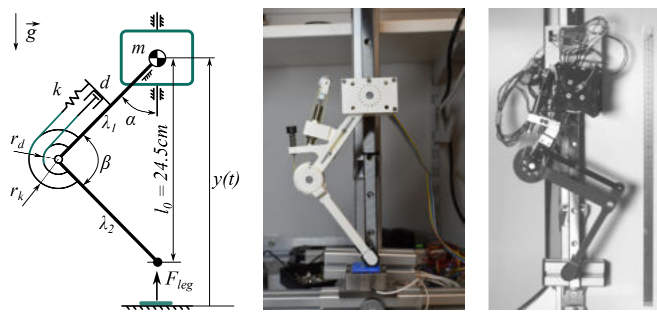
[1]Dynamic Locomotion Group, Max Planck Institute for Intelligent Systems, Stuttgart, Germany {mo}{izzi}{sprowitz}@is.mpg.de

[2]Hertie-Institute for Clinical Brain Research, University of Tuebingen, 72076 Germany daniel.haeufle@uni-tuebingen.de



(a) Leg model (b) 2-seg leg (c) 3-seg leg

Fig. 1. Robot leg with spring and damper parallel connected to the knee. (a) taken from [5].

In numerical simulation, we implemented a simplified leg model (Figure 1a) and characterized this system under different drop conditions: drop height, damping rate, and damping strategy. The simulation results indicate that an adjustable and viscous damper is desired to reject perturbations of the system's total energy due to variations in the drop height.

In hardware experiment, we developed the robot leg counterpart (Figure 1b) to characterize different dampers. By experimental design, we separated and quantified the measured dissipated energy during one drop cycle into its components: impact loss, viscous damping, Coulomb friction. We observed that hydraulic dampers are more effective than pneumatic dampers, and adjustable dampers exhibit complex mechanic responses when embedded into real legged systems.

To go beyond simple drop test, the next version of leg (Figure 1c) will be fully actuated to investigate neuromuscular damping strategies in hopping scenario.

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Questions around the catapult mechanism in human legged locomotion

Bernadett Kiss[1], Alexandra Buchmann[2], Daniel Renjewski[3], Alexander Badri-Spröwitz[4]

***Abstract*— The *swing leg catapult* is a key mechanism for high efficiency in human walking and shapes the natural leg dynamics. We aim to identify the components of the catapult system in the human leg with the help of neuromuscular simulations and a robotic model. The functional understanding of the mechanism could facilitate the improvement of gait rehabilitation devices and legged robots.**

Preferred type of presentation: Poster

Keywords: push-off, energy storage, power amplification, catapult, locomotion, biomechanics

I. Motivation and Problem Definition

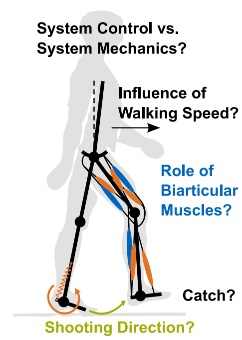
Our aim is to describe the components and the function of the catapult mechanism in human legs, and replicate it on a robotic model. Hof [1] was the first to propose that the ankle power burst during late stance of human gait is preceded by a slower energy storage phase which makes the human leg comparable to a catapult. Different types of catapult mechanisms were observed in other animals as well, such as horses [2], locusts, frogs, fleas, click beetles [3] and fish [4].

A catapult has three main components: an elastic component, a block, and a catch with or without escapement. The catch has been thoroughly studied in, for instance, locusts and frogs but has not been fully identified in the human leg yet. The release of the catch can be triggered by the imbalance of the internal and external moments around a certain body part or joint, [2] or by an active neural command [4].

Deeper understanding of the catapult mechanism bears great potential for improving orthoses, prostheses, legged robots, and could be leveraged in gait rehabilitation.

II. Related Work

The catapult's function in human locomotion is discussed controversially, i.e., what happens to the released energy. During touch-down of the leading leg collision losses arise which must be restored. Push-off work of the trailing leg could redirect the center of mass velocity and considerably reduce the effect of the collision if the knee joint's buckling just before push-off is not taken into account [5]. However, a flexed knee joint is assumed to transfer only a fraction of the push-off energy into the trunk, and with that in mind, push-off work could power leg swing instead [6].



III. Own Approach and Contribution

We want to develop a functional understanding of the catapult by combining two approaches: evolving a neuromuscular simulation model [7] and building a robotic model. Of particular interest is to understand the catch and release mechanism of the catapult and its transfer to technical systems. In our poster we will present the results of an extensive literature review, and first design suggestions.

Acknowledgment

Our project is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation)—3991/2.

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[1]Bernadett Kiss is a 1st year PhD student at the Dynamic Locomotion Group, Max Planck Institute for Intelligent Systems, Stuttgart, Germany kiss@is.mpg.de

[2]Alexandra Buchmann is a 1st year PhD student at the Chair of Applied Mechanics, Technical University of Munich, Germany; School of Engineering & Design, Department of Mechanical Engineering alexandra.buchmann@tum.de

[3]Daniel Renjewski is a lecturer at the Chair of Applied Mechanics, Technical University of Munich, Germany; School of Engineering & Design, Department of Mechanical Engineering daniel.renjewski@tum.de

[4]Alexander Badri-Spröwitz is the leader of the Dynamic Locomotion Group, Max Planck Institute for Intelligent Systems, Stuttgart, Germany sprowitz@is.mpg.de

Learning of Walking Gait Controllers for Magnetic Soft Millirobots

Sinan O. Demir[1,2], Utku Culha[1,3], Sebastian Trimpe[4,5] and Metin Sitti[1]

Abstract— **Untethered small-scale soft robots have promising applications in minimally invasive surgery, targeted drug delivery, and biomedical applications as they can directly and non-invasively access confined and hard-to-reach spaces in the human body. However, it is essential to have an adaptive control system for such potential biomedical applications to ensure the safety and the continuity of the operations due to inherent stochastic variability during fabrication, highly nonlinear soft continuum deformation kinematics, changing robot dynamics during real-world interactions, and dynamic variations in the task environment conditions. We propose utilizing a probabilistic learning approach using Bayesian optimization (BO) and Gaussian processes (GPs) to address this challenge. We further improve the learning performance by transferring the learned GP models among different robots and task spaces as prior information. We showed the learning approach's adaptation capability and data efficiency while optimizing the stride length performance of the walking soft millirobot within a small number of physical experiments. We tested our approach on three different robots and in different task environments with surface adhesion, roughness, and medium viscosity.**

Soft robotics, adaptive locomotion, transfer learning in Bayesian optimization with Gaussian Processes

I. Motivation and Problem Definition

Magnetic soft robots are composed of highly deformable soft materials with programmable shape change capability [1], which enable safe physical human-robot interaction due to their physical compliance and the mechanical dampening of excess forces [2]. Small-scale (i.e., ≤ 1 cm) magnetic soft robots have further potential application areas in medicine owing to their ability to access enclosed small spaces non-invasively [3] and the embodiment of functionalized materials enabling targeted drug delivery, diagnostics, and surgery [4]. Despite their potential biomedical applications, it is necessary to overcome some challenges arising from the nature of their soft materials, such as having virtually infinite degrees of freedom, nonlinear material behavior, being prone to fabrication errors, changing robot dynamics during real-world interactions, and dynamic variations in the task environment conditions. Therefore an adaptive controller is essential to ensure the continuity of the operations.

[1]Authors are with the Physical Intelligence Department, Max Planck Institute for Intelligent Systems, 70569 Stuttgart, Germany

[2]Author is in 3rd year of his Ph.D. at the Stuttgart Center for Simulation Science (SC SimTech), University of Stuttgart, 70569 Stuttgart, Germany

[3]Author is with the Munich School of Robotics and Machine Intelligence, Technical University of Munich, 80797 Munich, Germany

[4]Author is with the Intelligent Control Systems Group, Max Planck Institute for Intelligent Systems, 70569 Stuttgart, Germany

[5]Author is with the Institute for Data Science in Mechanical Engineering, RWTH Aachen University, 52068 Aachen, Germany

II. Related Work

Constant curvature [5], [6] and Cosserat rod [7] models are the most preferred methods to analytically model soft robotic systems' kinematics and dynamics. There are also numerical methods using finite-element methods (FEMs) [8], [9] and voxel-based representations [10] to improve the computation time at the expense of nonlinear dynamics precision. Even though these approaches allow the implementation of controllers for soft robots on a larger scale [11], they may not be used on small scales due to the lack of continuous sensing of body deformations, highly responsive actuators, and computationally heavy model solutions. Moreover, dynamic changes in their working environments, fabrication-based variations, and material degradation over time affect robotic function performances [3]. These challenges makes data-driven and adaptive control methods more desirable for untethered small-scale soft robots. For the data-driven methods, on the other hand, data efficiency, i.e., the ability to learn from small number of experiments, becomes crucial [12]. Bayesian optimization (BO) with Gaussian processes (GPs) is shown to maximize a given performance function in a data-efficient way without needing an explicit dynamics model [13], [14], [15].

III. Own Approach and Contribution

We propose a data-efficient learning procedure to find the optimum controller parameters of walking magnetic soft millirobots [16] within a limited number of physical experiments. As the used magnetic soft millirobots have performance inconsistencies due to the fabrication errors, material degradation over prolonged experiments, and environmental disturbances, we employed BO and GPs to learn the controller parameters while optimizing the average stride length of the robots. We also utilized the transfer of the learned GP models among different robots and task spaces as prior information. We tested our approach on three different robots and on task spaces with different surface roughness and friction, and liquid medium viscosity to emulate the conditions inside the human body. The main contributions of our study are:

- demonstration of BO that can efficiently learn the gait controllers of a small-scale untethered robot whose performance is prone to fabrication-, material-, and physical interaction-based variabilities;
- successful testing of the walking gait on three different task spaces that emulate, e.g., dynamic environments inside the human body, and the adaptation of the robot controller parameters to these environments in a small number of experiments.

Acknowledgment

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Rigid, Soft, Passive, and Active: a Hybrid Occupational Exoskeleton

Francesco Missiroli[1], Nicola Lotti[1], Enrica Tricomi[1], Casimir Bokranz[1], Ryan Alicea[1] and Lorenzo Masia[1]

***Abstract*— Physically demanding work is still common in the western countries, with large proportions of the workforce exposed for more than a quarter of their working time to tiring postures or repetitive tasks. Recent advancements in assistive technology provided new instruments to promote safety and reduce workload, colloquially referred as occupational exoskeletons (OE). OEs for upper limbs are usually single-joint exoskeletons and assist shoulder flexion/extension; they do not provide support to distal joints such as the elbow. In the present work, we combined a spring-loaded shoulder exoskeleton with an active elbow exosuit to extend the capability of the OEs to provide gravitational support to both shoulder and elbow flexion-extension in strenuous manual tasks.**

Preferred type of presentation: Oral presentation.

I. Motivation and Problem Definition

Work-related musculo-skeletal disorders (WMSDs) cover 60% of work-related injuries and are the most prominent health problem in the European Union (EU), affecting millions of workers and impacting the healthcare system with avoidable financial burdens [1]. In 2015, approximately three out of every five workers in the EU reported WMSD in the back, upper limbs and/or lower limbs [2] with a preponderance of backache and muscular pains in the upper limbs, followed by complications in the lower limbs.

II. Related Work

OEs are being developed with the aim to make work safer by reducing the effort of the shoulder muscles during tasks of overhead manipulation [3]. Upper-limb devices for supporting tasks of overhead manipulation are designed commonly using rigid (or semi-rigid) structures, with the aim to support occupational tasks involving arm elevation and overhead work (MATE, COMAU, Italy, ShoulderX from SuitX, USA and PAEXO, Ottobock, Germany). A common feature of those devices is that their assistance is restricted to the shoulder flexion-extension, with no supporting action for more distal joints such as the elbow articulation. Unfortunately, providing gravitational support to the elbow joint is not a simple engineering task since elbow gravitational torque is variable with both the elbow and shoulder posture.

III. Own Approach and Contribution

The developed hybrid exoskeleton, is a fully embedded system comprising of two modular and interconnected layers that can be worn independently: an actuated soft wearable exosuit that supports the elbows, and a passive occupational exoskeleton assisting the shoulders (i.e. *MATE*, COMAU). The sensing network for motion detection of the exosuit comprises four IMUs, communicating the tridimensional arm postures to the controller stage. We estimated a reference torque from a biomechanical model of the user, accounting for the tridimensional kinematics of the joints. This was then tracked by an admittance controller comparing the estimated torque with the torque delivered by the exosuit to the human joint. The error torque was then converted into a motor velocity command [4]. The experimental protocol involved a tracking of bimanual arm trajectories performed with and without the hybrid device holding a load of $1.5\,\mathrm{kg}$ on each wrist to simulate the use of a working tool. The device, successfully reduces muscular activation on the shoulders as well as the elbows: a reduction of 32% of *biceps* activation during elbow flexion has been reported and provided by the actuated layer and an average reduction of 31% of *deltoids* activation during shoulder abduction. Moreover, the co-contraction index of the main muscles involved in the elbow and shoulder motion, presents no statistical difference between the *No Exo* and *Exo* condition. In this study, we have demonstrated that active and passive assistance, if opportunely combined, can efficiently work to provide tangible improvement in terms of muscular efficiency.

Fig. 1. *Hybrid exoskeleton* developed to assist elbow and shoulder joints.

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[1]Francesco Missiroli, Nicola Lotti, Enrica Tricomi, Casimir Bokranz, Ryan Alicea, and Lorenzo Masia are with the Institut für Technische Informatik (ZITI), Heidelberg University, 69120 Heidelberg, Deutschland. francesco.missiroli@ziti.uni-heidelberg.de

Underactuated Soft Hip Exosuit Based on Adaptive Oscillators

Enrica Tricomi[1*], Nicola Lotti[1], Francesco Missiroli[1], Xiaohui Zhang[1], and Lorenzo Masia[1]

***Abstract*— Wearable devices to assist locomotion need to be lightweight and to adapt to the user's walking pattern. To tackle these features, we developed an underactuated soft hip exosuit incorporating a control framework based on Adaptive Oscillators to deliver flexible assistance. Preliminary results on six healthy subjects show good tracking of users' gait pattern and symmetrical bilateral delivered assistance. Muscular assessments revealed a decreasing trend in the effort required for motion; a slight alteration of hip kinematics resulted only at slow walking speed. Once further validated, the device can be used in clinical and wellness applications.**

Preferred type of presentation: Oral presentation

I. Motivation and Problem Definition

Human locomotion mechanisms are hard to imitate: walking requires coordination of multiple joints to minimize body effort and energy consumption [1]. Therefore, when dealing with assistive technologies design, main requirements should include lightness and compactness from the hardware viewpoint, and adaptation to changes in walking pattern from the controller perspective. Most of the current state of the art wearable robotic solutions adopt one actuator for each controlled degree of freedom to finely modulate assistance in multiple joints, yet influencing the complexity and overall weight [2]. In addition, in the case of walking, most of the formulated control schemes relies on a complex sensory network affecting system intuitiveness and promptness, besides being sometimes distant from mimicking natural locomotion.

II. Related Work

Recent trends in soft robotics have foreseen the use of fewer independent actuators than the number of controlled joints. Underactuated devices stand out for reduced weight, and simpler mechanical and control designs, while still able to assist a wide range of movements. Although several examples of underactuated soft robotic devices exist for upper-limb [3], very few solution exist for lower-limb assistance. Besides, most of them use underactuation to synergistically assist multiple joints, still decoupling the two legs.

III. Own Approach and Contribution

To combine simplicity and lightweight we developed a fully embedded wearable exosuit to assist hip flexion during walking (Fig. 1). The device is underactuated, i.e., a single actuator is used to assist bilateral hip flexion. The user is assisted through two artificial tendons wrapped in opposite directions on a double-layer pulley mounted on the motor. To provide adaptive assistance, we adopted a control strategy based on Adaptive Oscillators and the gait phase estimator described in [4] on the High-Level controller. The control algorithm is solely driven by IMU sensors recording the hip flexion angle. A Low-Level controller converts the gait phase information into motor velocity command according to the motion: assistance is provided to each leg only during swing. The system was tested on six healthy subjects with treadmill evaluations at variable and constant walking speed (0.4, 0.7, and $1.0\,\mathrm{m/s}$). Main investigations concerned device performance to adapt to the tested walking speeds and delivered assistance to both legs, along to preliminary assessments of changes in users' kinematics and lower-limb muscle effort. Main outcomes showed fast adaptability of the control algorithm to new walking conditions and balanced assistive torque delivered to both legs by the underactuated mechanism. Despite a slight increase of hip peak velocities only at $0.4\,\mathrm{m/s}$, muscular investigations revealed a decreasing trend in muscle effort using the exosuit (nearly 20%). Given the emerging interest in soft assistive robotics, we believe that our device might be suitable to target different categories of individuals, from healthy subjects to mild impaired people.

Fig. 1. *Underactuated Hip Exosuit*

[1]Enrica Tricomi, Nicola Lotti, Francesco Missiroli, Xiaohui Zhang, and Lorenzo Masia are with the Institut für Technische Informatik (ZITI), Heidelberg University, 69120 Heidelberg, Deutschland

∗ corresponding author: enrica.tricomi@ziti.uni-heidelberg.de

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The benefit of muscle-actuated motion in optimization and learning

Isabell Wochner[1] and Syn Schmitt[1]

Abstract— **Humans have the remarkable ability to control a wide variety of movements in uncertain environments. To do so, they rely on their specific biomechanical structure, which provides inherent stability. While many previous studies have investigated the control of these movements in simulations and robotics, they have largely neglected the highly nonlinear muscle dynamics. To address this, we use optimal control to exploit the morphology of the biomechanical system and compare it to other morphologies such as idealized torque actuators. Our key idea is to compare and optimize three different tasks: A point-reaching movement with a two-joint arm, a squatting movement and a high-jump task with a whole-body model. We show that using muscle-actuated motion can simplify the control problem because a good enough optimum can be found with fewer iterations, which reduces the computational cost. The main reason for this is the nonlinear force-velocity relation of the muscles.**

Preferred typ of presentation: Oral
Keywords: morphological computation, limited resources

I. Motivation and Problem Definition

Muscle-actuated systems pose the problem of a high-dimensional state space with highly nonlinear characteristics due to their complex contraction and activation dynamics and their nonlinear antagonistic setup, including nonlinear moment arms. From a technical control perspective, these system properties are challenging, which makes finding suitable control schemes difficult. Nevertheless, humans have the ability to perform versatile movements, which leads us to the question whether the biological motor system has properties that also facilitate the control task as well as the optimization and learning of movements.

II. Related Work

Previous work introduced the concept of morphological computation: The idea behind this concept is that the morphology of the actuated system can contribute to the movement generation and thus reduces the neural information and processing load, which otherwise would have to be performed by some high-level controller. It was shown in previous studies that muscle-actuated systems have the advantage of reducing neural information load compared to torque-actuated systems while performing the same movement [1]. Different studies showed that muscle properties reduce the effect of small disturbances, e.g. in human vertical jumping [2] or walking [3] to such a degree that it is not necessary to adapt the optimized stimulation pattern compared to torque-driven actuators. The reason behind this is that muscles provide inherent robustness due to their specific morphology. While some of the previously named studies typically applied minimalistic control architectures, it was shown by [4] that using optimal control methods, the dependence between the control architecture and the morphology of the robot can be eliminated. Furthermore, they showed that it would not have been possible to evaluate and compare different morphologies with a more naive control architecture such as a constant linear feedback controller.

[1]Isabell Wochner and Syn Schmitt are with the Institute for Modelling and Simulation of Biomechanical Systems, University of Stuttgart, Stuttgart, Germany isabell.wochner@simtech.uni-stuttgart.de

III. Own Approach and Contribution

We used an optimal control method using the covariance matrix adaptation evolution strategy (CMA-ES) as optimization method to compare three different tasks: a point-reaching movement, a squatting movement and a high-jump task. As actuators, a Hill-type muscle model, as well as idealized torque actuators, were used. We show that optimizing muscle-actuated motion is beneficial because a good enough optimum is found with fewer iterations. This trade-off between performance and computational cost is especially significant in biological motion when considering the limited resources available to the human body. The main reason for this benefit is that the optimizer can rely on the self-stabilizing dynamical properties of the muscles. This property is mainly exhibited by the nonlinear force-velocity relation in the muscle model, which has the strongest effect on the performance of the optimization.

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Extracting Strong Policies for Robotics Tasks from Zero-Order Trajectory Optimizers

Sebastian Blaes, Cristina Pinneri, Georg Martius
Autonomous Learning Group, Max Planck Institute for Intelligent Systems, Germany, Tübingen

Solving high-dimensional, continuous robotic tasks is a challenging optimization problem. Model-based methods that rely on zero-order optimizers like the cross-entropy method (CEM) [4] have so far shown strong performance and are considered state-of-the-art in the model-based reinforcement learning community. However, this success comes at the cost of high computational complexity, being therefore not suitable for real-time control.

We propose APEX, a technique to jointly optimize the trajectory and distill a policy, which is essential for fast execution in real robotic systems. Our method builds upon an improved version of CEM (iCEM) [2] and standard approaches, like guidance cost [1] and dataset aggregation [3], and introduces a novel adaptive factor which prevents the optimizer from collapsing to the learner's behavior at the beginning of the training.

The extracted policies reach unprecedented performance on challenging tasks like making a humanoid stand up and opening a door without reward shaping, as shown in the Fig. 1.

Figure 1: Environments and exemplary behaviors of the learned policy using APEX. From left to right: Fetch Pick&Place (sparse reward), Door (sparse reward), and Humanoid Standup.

In Fig. 2, we compare APEX against several imitation learning baselines. Only our method manages to solve all tasks to full satisfaction. Note that we use partially sparse rewards settings in Fetch Pick&Place (only box-to-goal reward) and Door (sparse reward) (no hand-to-handle reward) which makes them particularly challenging.

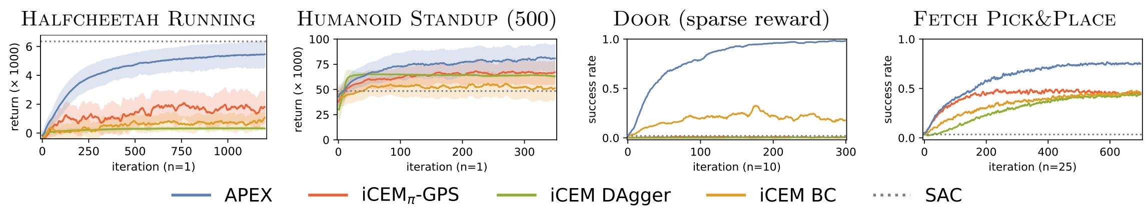

Figure 2: Policy performance on the test environments for APEX and baselines. SAC performance is provided for reference.

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Specializing Versatile Skill Libraries using Local Mixture of Experts

Mevlüt Onur Celik[1,2], Dongzhuoran Zhou[3], Ge Li[1,2], Philipp Becker[1,2], Gerhard Neumann [1,4]

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Abstract— **A long-cherished vision in robotics is to equip robots with skills that match the versatility and precision of humans. Starting from Mixture of Experts (MoE) model and maximum entropy reinforcement learning (RL), we decompose the versatile-skills learning objective into optimizing an individual lower bound per mixture component, where each expert represents a contextual motion primitive. Further, we introduce a curriculum by allowing the components to focus on a local context region, enabling the model to learn highly accurate skill representations. To this end, we use local context distributions that are adapted jointly with the expert primitives. Our lower bound advocates an iterative addition of new components, where new components will concentrate on local context regions not covered by the current MoE. This local and incremental learning results in a modular MoE model of unprecedented accuracy and versatility, where both properties can be scaled by adding more components on the fly. We demonstrate this by an extensive ablation and on two challenging simulated robot skill learning tasks. The original paper [1] of current work has already been accepted by the Conference on Robot Learning (CoRL) 2021.**

Preferred type of presentation: Poster

I. Motivation and Problem Definition

When playing table tennis, human players are capable of returning the ball in various ways while precisely placing it at a desired location. Similarly, such versatile skills are crucial if we want to employ robots in unstructured and dynamically changing environments. Such skills, often represented as movement primitives, were already successfully learned for challenging robot learning task by a variety of policy search algorithms [2]. Such algorithms, with an assumption of Gaussian policy, however, suffer from finding multiple, versatile, and precise solutions to the multi-modal solution space. In this paper, we model versatile behavior with contextual skill libraries of motion primitives [3], formalized by Mixtures of Experts (MoEs).

II. Related Work

Contextual Episodic Policy Search. Episodic policy search [2] aims at maximizing the expected return by optimizing the parameters of a controller.

Versatile Skill Learning. The Hierarchical Relative Entropy Policy Search (HiREPS) algorithm [4] extends the classical Relative Entropy Policy Search (REPS) approach [5] to MoEs, which allows learning versatile skills in a contextual episodic policy search setting.

Variational Inference. Our algorithm is also based on several recent advances in variational inference [6], [7], [8]. It is well known that maximum entropy RL is equivalent to inference in an appropriate probabilistic model [9]. Similar to previous works [10], [11], we exploit this relation and draw inspiration from recent research into variational inference and density estimation for Gaussian mixture models and MoEs.

III. Own Approach and Contribution

We propose a new objective for learning MoE models based on a maximum entropy formulation. This objective also introduces a learnable context distribution, which provides a curriculum for the MoE model and can be decomposed into individual updates for the components and their related local context distributions. This allows the components to specialize in local regions of the context space and prevents mode averaging. We demonstrate that we can learn versatile and precise contextual motor skills in simulated beer pong and table tennis environments (Fig.1) while cover the context space properly. Moreover, we present ablation studies showing the importance of the single elements and hyperparameters of our algorithm and show the quality of our solution. Please refer the original paper [1] of current work for more details.

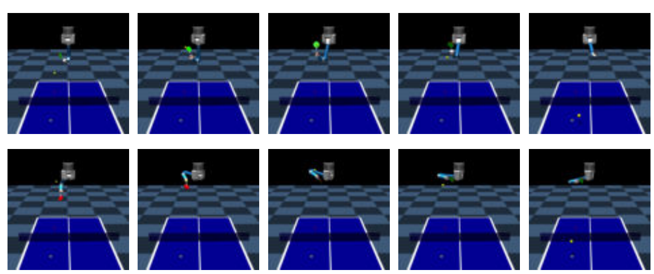

Fig. 1: **Table Tennis Experiment.** Forehand and backhand strikes given same incoming ball context.

[1]Institute for Anthropomatics and Robotics (IAR), Karlsruhe Institute of Technology (KIT), Germany.
[2] Second-year PhD students.
[3] Master student of KIT.
[4] The Group leader of Autonomous Learning Robots Lab, IAR, KIT.

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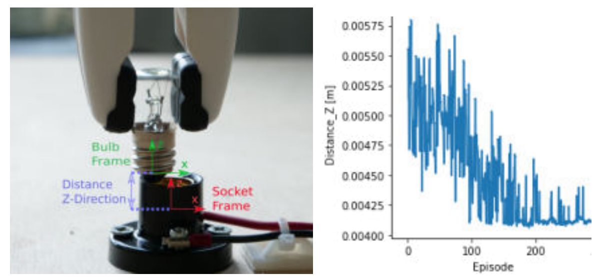
Combining Manipulation Primitive Nets and Policy Gradient Methods for Learning Robotic Assembly Tasks

Marco Braun[1,2] and Sebastian Wrede[1]

***Abstract*— Autonomous learning of robotic assembly tasks is a promising proposition for industrial manufacturing. Although a lot of research is being done in this area, sample efficiency in particular is a problem for Reinforcement Learning methods. We present a grey-box learning approach that enables process experts to provide a partial but possible incomplete behavior description based on Manipulation Primitive Nets. These Manipulation Primitive Nets are extended with learning capabilities by introducing choice states. Our framework called Adaptive Manipulation Strategies (AMS) is evaluated in a real-world light bulb robotic assembly process. It is shown that dexterous insertion of the light bulb can be learned with comparatively few real-world trials.**

Preferred typ of presentation: Oral
Robotic Assembly, Robot Learning, Automation



(a) Light Bulb Assembly Task (b) Learning Progress

Fig. 1: Robot learns to align a light bulb with the socket frame, wheras upstream and downstream process steps are fully specified based on MP-Nets.

I. Motivation and Problem Definition

Robot-based automation of assembly processes is a challenging problem. Especially contact-rich interactions are hard to specify with classical methods and a lot of manual optimization is necessary to achieve robust performance. In addition, there is often the use case that component poses are detected with the help of camera technology and are then to be assembled in order to make production more flexible. For precise assembly processes that require high accuracy, positional uncertainties due to pose estimation errors must be compensated. RL based methods are a promising solution, but learning from scratch usually requires a lot of samples. Therefore, incorporating prior knowledge is key to making learning-based methods tractable.

II. Related Work

Classical approaches focus on specification of robotic manipulation processes. Hybrid force- and position controlled motions have been formalized by Mason [1] with the Task Frame Formalism (TFF). Finkemeyer et al.[2] introduced Manipulation Primitive Nets (MP-Nets) that allow for specification of complex manipulations tasks that require sensor-based control based on the TFF. The coordination of MPs is modeled based on state-machines.

Thomas et. al [3] present a policy search approach supported by prior knowledge for robotic assembly tasks. Here, special properties of industrial assembly processes are used to simplify the learning problem. Usually, CAD data is available and the geometry of the parts to be assembled is known in advance. Furthermore, the environment is structured and well defined. On this basis, collision-free motion plans are calculated, which are used to compute a reward function.

III. Own Approach and Contribution

We propose a grey-box learning approach that integrates specification and learning in a common modeling framework. Process expert model a partial behavior description based on MP-Nets, that are extended with non-deterministic choice states inspired by the Hierarchies of Abstract Machines (HAM) [4] framework to enable learning. Learning the coordination of MPs in choice states bases on the Proximal Policy Optimization (PPO) [5] algorithm. Our approach is evaluated in an threaded light bulb assembly task see Figure 1. It is shown, that an dexterous alignment behavior based on force-sensor data is successfully learned after about 200 real-world trials which corresponds to half on hour of interaction.

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[1] Research Institute for Cognition and Robotics, Bielefeld University, Germany {m.braun, sebastian.wrede}@uni-bielefeld.de

[2] Third year PhD student

Robot Dynamics Learning with Action Conditional Recurrent Kalman Networks

Vaisakh Shaj[1,2], Philipp Becker[1,2], Gerhard Neumann [1,4]

Abstract— **Estimating accurate forward and inverse dynamics models is a crucial component of model-based control for sophisticated robots. A promising approach is to obtain spatio-temporal models in a data-driven way using recurrent neural networks, as they can overcome several challenges in robot dynamics learning like hysteresis, unmodelled stiction, friction, contact dynamics etc. We adopt a recent probabilistic recurrent neural network architecture, called Recurrent Kalman Networks (RKNs), to model learning by conditioning its transition dynamics on the control actions. Inspired by Kalman filters, the RKN provides an elegant way to achieve action conditioning within its recurrent cell by leveraging additive interactions between the current latent state and the action variables. We present two architectures, one for forward model learning and one for inverse model learning. Both architectures significantly outperform existing model learning frameworks as well as analytical models in terms of prediction performance on a variety of real robot dynamics models.**

Preferred type of presentation: Poster

I. Motivation and Problem Definition

Dynamics models are an integral part of many control architectures. Depending on the control approach, the control law relies either on a causal forward model or an anti-causal inverse dynamics models. Most often, analytical dynamics models are either not available or often too inaccurate in situations such as robots driven by hydraulics, artificial muscles, or robots dealing with unknown contact situations. Additional challenges for modelling are given by the high data frequency, often up to 1kHz. Furthermore, many modern model-based architectures for learning controllers rely on uncertainty estimates of the prediction. Hence, such probabilistic modelling ability is another point on the desiderata for model learning algorithms. In this paper, we extend a recent probabilistic recurrent neural network architecture [1],, called Recurrent Kalman Networks (RKN), for learning forward and inverse dynamics models.

II. Related Work

Robot Dynamics Learning: Traditional model learning methods like Linear Regression [2][3], Gaussian Mixture Regression [4][5], Gaussian Process Regression [6][7], Support Vector Regression [8], and feed forward neural networks [9] fails in non-markovian systems used in modern robotics which we benchmark on.

[1]Institute for Anthropomatics and Robotics (IAR), Karlsruhe Institute of Technology (KIT), Germany.

[2] Second-year PhD students.

[4] The Group leader of Autonomous Learning Robots Lab, IAR, KIT.

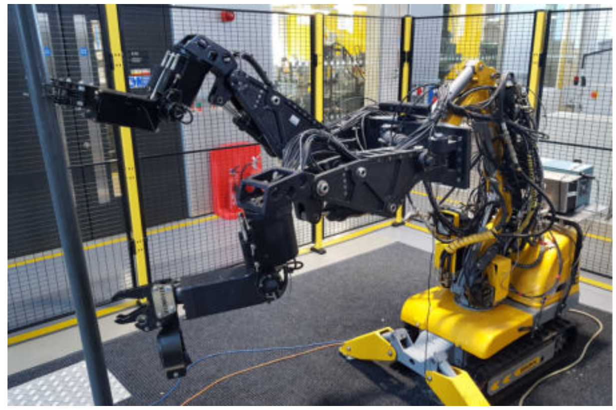

Fig. 1: **Brokk Manipulator:** One of the robots with a non-markovian dynamics that we benchmarked AcRKN on.

Action-Conditional Probabilistic Models The action conditioning in model learning literature for recurrent models is realized by concatenating the input observations and action signals or via factored conditional units. In each of these approaches action conditioning happens outside of the recurrent neural network cell which leads to sub-optimal performance as observations and actions are treated similarly. We show the superior performance of a disentangled state and action representation.

III. Own Approach and Contribution

We introduce a probabilistic recurrent neural network architecture, called action-conditional Recurrent Kalman Networks (ac-RKN), capable of action conditioning within the recurrent cell in a principled manner using additive interactions of state and action signals in the recurrent cell. This formulation allows us to learn highly accurate forward dynamics models of sophisticated robots and scenarios for which analytical models do not exist.

We demonstrated the effectiveness of the proposed approach on robots with hydraulic, pneumatic and electric actuators. Besides, we leveraged the action-conditional recurrent cell to propose a regularized inverse dynamics model which significantly outperformed the current state of the art on two benchmarks. We believe the disentangled representation of the control signal in the ac-RKN recurrent cell has the potential to be exploited for several other robot learning problems. Also, since our architecture is domain-independent, we expect that they will generalize to several other robot dynamics learning tasks. Please refer the original paper [10] of the current work for more details.

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Seamless Sequencing of Skills via Differentiable Optimization

Noémie Jaquier, You Zhou, Julia Starke, and Tamim Asfour

***Abstract*— In contrast to humans and animals that naturally execute seamless motions, learning and smoothly executing sequences of actions remains a challenge in robotics. This extended abstract introduces a novel skill-agnostic formulation that learns to sequence and blend skills based on differentiable optimization. Our approach leverages quadratic programs and differentiable optimization layers to learn and generate seamless sequences of skills from demonstrations. We showcase our formulation in a pouring experiment with a humanoid robot.**

I. Motivation and Problem Definition

This extended abstract aims at learning and executing seamless sequences of robotic actions. In the following, we assume a set of previously-trained individual robotic skills (e.g., a skill library). The skills are considered as given black-box solutions, implying that their representations are unknown and may differ across the skills. At each instant, each skill outputs a desired control value $\hat{\boldsymbol{\xi}}_k$ to be given to the robot. We then consider a manipulation task consisting of an *unknown* sequence of the skills, possibly concurrently activated. We observe *optimal* demonstrations of the task.

II. Related Work

Sequencing approaches presented in the literature are specifically tailored to a single skill type (e.g., [1], [2]). Moreover, transitions are usually handled by matching the end- and start-points of subsequent skills, and are thus characterized by obvious pauses. In contrast, our approach is *skill-agnostic* and learns sequences featuring *seamless and natural* transitions. Sequencing and blending of tasks has also been explored in the context of robot multitask control, where smooth transitions are achieved by varying the relative importance of skills [3]. Our work distinguishes in that we directly learn the relative importance of skills along the task by *differentiating* through the optimization problem.

III. Own Approach and Contribution

Similarly to multitask control, we propose to encode sequences of skills as QPs. Namely, given the desired control values $\{\hat{\boldsymbol{\xi}}_k\}_{k=1}^K$ output by the K individual skills and the current control values $\{\boldsymbol{\xi}_k\}_{k=1}^K$, a sequence of skills can be generated by solving the following optimization problem

$$\min_{\{\boldsymbol{\xi}_k\}_{k=1}^K} \frac{1}{2} \begin{pmatrix} \hat{\boldsymbol{\xi}}_1 - \boldsymbol{\xi}_1 \\ \vdots \\ \hat{\boldsymbol{\xi}}_K - \boldsymbol{\xi}_K \end{pmatrix}^\mathsf{T} \boldsymbol{W}(s) \begin{pmatrix} \hat{\boldsymbol{\xi}}_1 - \boldsymbol{\xi}_1 \\ \vdots \\ \hat{\boldsymbol{\xi}}_K - \boldsymbol{\xi}_K \end{pmatrix}, \qquad (1)$$

Fig. 1: Pouring task with ARMAR-6 and hand position trajectories.

at each $s \in [0, 1]$, where $\boldsymbol{W}(s)$ is a varying weight matrix setting the relative importance of the skills throughout the sequence in function of the phase variable s encoding the task progress. The problem (1) is augmented with linear constraints related to the robotic system. Importantly, the skill ordering in (1) is arbitrary. Indeed, the sequence is defined by the varying $\boldsymbol{W}$, which is learned from demonstrations.

Given some demonstrations of a manipulation task, we aim at learning the skill weight function $s \mapsto \boldsymbol{W}(s) : \mathbb{R} \to \mathcal{S}_+^n$, so that the reproduction, i.e., the sequence of skills obtained by solving (1) for $s \in [0, 1]$, replicates the demonstrated task. This corresponds to minimizing a loss function ℓ measuring the quality of the reproduction. To do so, we need to solve a nested optimization: For each time instance of the task, we solve (1), and the whole set of solutions $[\{\boldsymbol{\xi}_{k,s}^*\}_{k=1}^K]_{s=0}^1$ is then used to minimize the loss ℓ. To solve this problem, we leverage Optnet [4] to integrate the QP (1) into a neural network. Optnet allows us (*i*) to represent the QP parameters as functions, and (*ii*) to differentiate ℓ with respect to the QP parameters to solve the outer optimization of our nested problem using gradient-based approaches. In other words, Optnet backpropagates the loss ℓ to optimize both the phase-dependent skills weights $\boldsymbol{W}(s)$ and the control outputs $\boldsymbol{\xi}_k$.

We showcase our approach by learning a complex sequence of skills with ARMAR-6 [5]. The scenario consists of a pouring task, encoded with a set of 7 skills provided as black-box solutions (`approach`, `pour`, `place the bottle back`, `retreat the arm`, `open` and `close the hand`), for which our approach was trained on 7 manually-designed demonstrations. Our approach not only succeeds at learning the desired sequence of skills, but also results in seamless transitions as indicated by the smoothness of the trajectories (Fig. 1).

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The authors are with the Institute for Anthropomatics and Robotics, Karlsruhe Institute of Technology, Karlsruhe, Germany. {noemie.jaquier, asfour}@kit.edu

Learning Control Policies from Optimal Trajectories

Christoph Zelch[1], Jan Peters[2], Oskar von Stryk[1]

Abstract— **The ability to optimally control robotic systems offers significant advantages for their performance. While time-dependent optimal trajectories can numerically be computed for high dimensional nonlinear system dynamic models, constraints and objectives, finding optimal feedback control policies for such systems is hard. We learn a feedback control policy from a set of optimal reference trajectories using Gaussian processes. Information from existing trajectories and the current policy is used to find promising start points for the computation of further optimal trajectories.**

The method has been applied in simulation to a swing-up problem of an underactuated pendulum and an energy-minimal point-to-point movement of a 3-DOF industrial robot.

Preferred typ of presentation: Oral presentation

I. Motivation and Problem Definition

Optimal control theory enables the formulation of optimality criteria and provides a basis for numerical methods that enable the offline, model-based computation of optimal trajectories even for large-scale nonlinear robot dynamics models, nonlinear cost functions as well as nonlinear state and control constraints. Good nonlinear robot dynamics models are often available and enable deep insights in the system's dynamic behavior which can be only fully utilized by an optimal control approach. However, for practical applications, even small model inaccuracies as well as inevitable external disturbances or small deviations from the start position lead to deviations from the precomputed trajectory. These must be dealt with in a non-optimal manner, e.g., by real-time trajectory tracking controllers. This motivates the search for a near-optimal policy, that allows to proceed in real-time even under disturbances acting on the system.

Approaches of machine learning to find a near-optimal policy usually do not account for the capable model-based numerical trajectory optimization methods. However, some of these provide valuable information that can be highly beneficial to be utilized for the learning process.

II. Related Work

Generalization of trajectory data with a neural network is explored by Pesch et al [1]. They use analytical solutions as input for the neural network, but did not investigate the selection of start points for the optimal trajectories further.

In contrast, Atkeson et al. [2] explore the advantages of successive selection of start points. To improve Differential Dynamic Programming on global optimization problems, they compute trajectories from different start positions, using a number of acceptance criteria and generalize to a global control policy by using the nearest sampled state.

Baranes et al. focus on the selection of new training tasks for learning of parameterized policies for families of tasks [3]. They present an algorithm based on a measure of interest to actively select new training tasks to explore the task space.

III. Own Approach and Contribution

To learn a policy for a given problem formulation, we use information collected from optimal trajectories for different start points in the state space. These trajectories are generated using DIRCOL to solve optimal control problems.

The control values from the discretized trajectories are used to train a Gaussian process, which serves as non-parametric approximation of the optimal control policy. A Gaussian process has the advantage that it provides for each point a variance which serves as measure of uncertainty.

The selection of new start points is highly relevant for the "exploration" of unknown areas of the state space. It is important to acquire more information in regions of the state space, where a deviation from the optimal trajectory causes a significant change in the total cost of the executed path. We use an iterative approach that allows to continually supervise the improvement of the policy, select new start points based on information provided by co-states as an indicator for sensitive regions based on the variance of learned policy.

An optimal feedback control of dynamic systems to handle unknown disturbances is computationally expensive to obtain for most problems. We iteratively improve a policy with samples from optimal trajectories. With a new strategy of start point selection using information from existing trajectories, we are able to avoid full sampling of the joint space. We proposed an alternative to random sampling that uses information provided by the co-states of the optimal feed-forward solutions and the covariance of the learned policy.

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[1]Christoph Zelch and Oskar von Stryk are with the Simulation, Systems, Optimization and Robotics Group, Department of Computer Science, TU Darmstadt, Hochschulstr. 10, 64289 Darmstadt, Germany {zelch, stryk}@sim.tu-darmstadt.de

[2]Jan Peters is with the Intelligent Autonomous Systems Group, Department of Computer Science, TU Darmstadt, Hochschulstr. 10, 64289 Darmstadt, Germany jan.peters@tu-darmstadt.de

Residual Feedback Learning for Contact-Rich Manipulation Tasks with Uncertainty

Alireza Ranjbar[1,2,3] Ngo Anh Vien[3] Hanna Ziesche[3] Joschka Boedecker[1] Gerhard Neumann[2]

***Abstract*— While classic control theory offers state of the art solutions in many problem scenarios, it is often desired to improve beyond the structure of such solutions and surpass their limitations. We propose a new formulation that addresses the limitations of available approach by also modifying the feedback signals to the controller with an RL policy and show superior performance. In addition, we use a recent Cartesian impedance control architecture as the control framework which can be available to us as a black-box while assuming no knowledge about its input/output structure. A video showing the results can be found at `https://youtu.be/SAZm_Krze7U`.**

Preferred type of presentation: Oral

Improving beyond controllers' underlying structure

I. Motivation and Problem Definition

In many problem settings improving over available solutions appears more applicable than learning skills from scratch. Especially when samples are expensive, more guarantees are necessary, or the need for a solution is perceived more crucial than discovery while engineering costs are undesirable as well. Residual policy learning (RPL) [1], as one of possible solutions in this regard, suggests a formalism where the reinforcement learning (RL) agent learns to compensate for the imperfections of the up-stream controller by superposing its actions with it. Yet, the up-stream controller in many cases sees the intervention of the RL policy as external perturbation and error, and therefore tries to resist it. Fig. 1 (b) for example illustrates such scenario on the left where an ideal RL policy applies force toward the optimal direction while the controller has a different goal. The question remains however/

II. Related Work

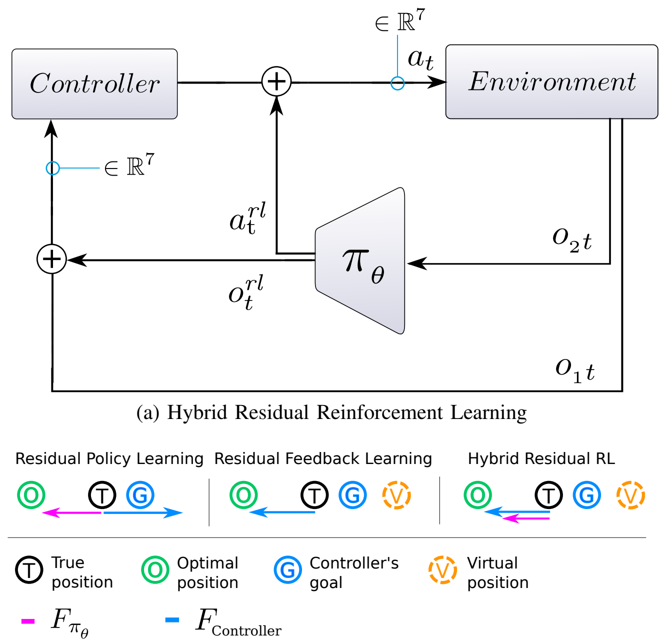
Two main concurrent works [1] and [2] demonstrated the residual policy learning (RPL) formulation and highlighted advantages such as sample efficiency, better sim-to-real adaptation, as well as the ability in handling sensor noise and controller miscalibration. A follow-up work [3] developed this idea further using visual inputs and sparse rewards for industrial insertion tasks.

III. Own Approach and Contribution

In this case, one can instead modify the feedback to the controller and obtain different results. In addition, in places where each formulation has its own advantage, combining both, i.e. an RL policy that outputs the residual controls as well as residual feedback commands, allows leveraging the distinct advantages of both methods simultaneously in one framework.

Our primary contributions are as follows: i) We propose an alternative and an extension to the RPL formulation [1] to address its limitations for a wide range of tasks and controllers. ii) We extend the manipulation framework of [4] using our approach and illustrate its distinct advantages iii) An empirical evaluation of the original method and ours along with their variants on simulation and hardware.

Affiliations with
[1] Albert-Ludwigs-Universität Freiburg
[2] Karlsruhe Institute of Technology
[3] Bosch Center for Artificial Intelligence (BCAI)



(a) Hybrid Residual Reinforcement Learning

(b) Expected behaviour of each Residual policy formulation

Fig. 1: (a) HRRL that is RPL combined with RFL. (b) While RPL regards the intervention of the RL policy as external perturbation and error, RFL changes the goal itself through feedback, that is for example, the controller sees the virtual feedback.

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Learning and Teaching Multimodal Neural Policies for Dexterous Manipulation

Philipp Ruppel[1], Norman Hendrich[1], Jianwei Zhang[1]

***Abstract*— We present methods for learning and teaching multimodal neural policies for robotic dexterous manipulation. Our imitation learning framework enables humans to teach manipulation tasks to robots by simply demonstrating the desired behavior with their own hands and real objects. Task information can be inferred from data. We can also train our networks from scratch with simulated differentiable physical consistency and without demonstrations. To improve tactile integration, we develop stretchable tactile sensor skin for robots and wearables.**

Preferred type of presentation: Poster

I. Motivation and Problem Definition

Human manual intelligence still far surpasses that of current robotic systems. To make robotic manipulation applicable to a larger set of problems and accessible to a wider user base, we want to enable humans to teach manipulation tasks to robots in intuitive ways, while reducing computational cost, and making the robot automatically adapt to new situations.

II. Related Work

Industrial robots can be moved manually into different configurations to record and replay poses. Researchers have proposed new methods to represent and recall recorded trajectories [1]. Adapting to sensor input and modified object poses typically still requires task-specific programming. Other methods allow robots to learn manipulation policies in simulation, but require specialized programming skills to set up simulation environments and to specify rewards [2]. It is also possible to optimize robot trajectories using virtual models and goal descriptions [3] [4]. While for some modalities, good sensors are already available, tactile sensing is still a topic of active research [5].

III. Own Approach and Contribution

We record motions and tactile sensations while human teachers demonstrate manipulation tasks with their own hands and real objects. We then train neural policy networks to imitate the human behavior. We use a combination of built-in invariances and randomization to generalize to new situations. The network is able to adapt to multiple objects with modified poses and can learn to generate trajectories that stretch from one object to another. The policies are trained on automatically generated point-based template models, so it is not necessary to manually design task-specific simulation models. With recurrent network architectures, we can learn long-running tasks with multiple sub-problems. We transfer the learned behavior to real robots via online trajectory optimization, enforcing safety constraints and avoiding collisions. The neural network can focus on manipulation tasks and is independent of a particular robot.

To improve tactile integration, we develop stretchable artificial skin with capacitive force sensing, which is made from elastic polymers, can be produced on double-curved freeform surfaces, and is suitable for both robots and wearables

In some cases, it may still be desirable to autonomously discover manipulation strategies from scratch in simulation. We found that some of our networks can be trained efficiently in virtual environments without demonstrations. The network predicts contacts and we simultaneously optimize for task goals and physical consistency.

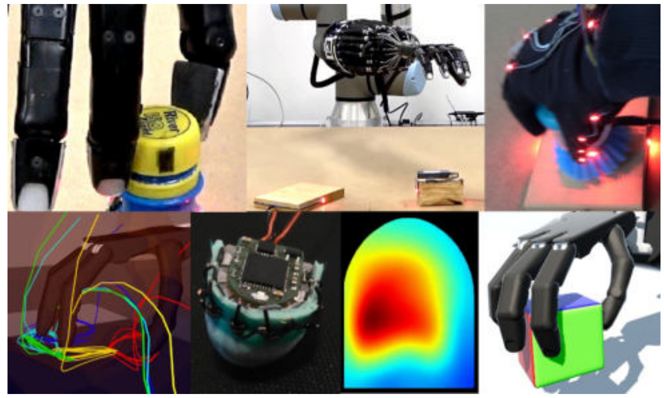

Fig. 1. Opening a bottle (top-left) and pick-place (top-center) via imitation learning, teaching a wiping task (top-right), Cartesian commands from the policy network and robot trajectory optimization (bottom-left), wearable elastic fingertip and output (bottom-center), learning manipulation tasks from scratch in simulation (bottom-right).

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[1]Authors are with Department of Informatics, Universität Hamburg, Hamburg, Germany {ruppel, hendrich, zhang}@informatik.uni-hamburg.de

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Robot Hand Dexterous Manipulation by Teleoperation with Adaptive Force Control

Chao Zeng and Jianwei Zhang

***Abstract*— This work focuses on improving the robot's dexterous capability by exploiting visual sensing and adaptive force control. A vision-based teleoperation learning framework, TeachNet, is used to map human hand postures to a multi-fingered robot hand. Our compliance controller takes the mapped robotic joint angles from TeachNet as the desired goal and computes the desired joint torques. It is derived from a computational model of the biomimetic control strategy in human motor learning, which allows us to adapt the control variables (impedance and feedforward force) online during the execution of the reference joint angle trajectories. The simultaneous adaptation of the impedance and feedforward profiles enables the robot to interact with the environment in a compliant manner.**

Preferred typ of presentation: Interactive

I. Motivation and Problem Definition

We propose a learning-control approach combining a vision-based teleoperation system with adaptive force control, allowing us to take an image as the input and output the desired force commands for the robot hand. Moreover, the controller must adapt the dynamics profiles in a real-time manner to enhance the compliant behaviors.

II. Related Work

Recent studies illustrate that object-level impedance control strategies increase the grasping stability and robustness citeficuciello2019vision,li2014learning. However, an object-level impedance controller may not be suitable for our use in a vision-based teleoperation system, where the controller needs to dynamically and quickly respond to the changes of the human hand pose to predict the desired force commands. Consequently, this work explores the regulation of the impedance (stiffness) and the feedforward term online during the process of robot grasping or manipulation, which cannot be learned in advance or through exploration.

III. Own Approach and Contribution

See Fig. 1, we employ the end-to-end model TeachNet developed in this previous work [4] to learn the mapping relation between the human hand pose and the joint angles of the Shadow robot hand. We develop an adaptive force control strategy that can predict the desired next-step control force command based on the desired joint angles and the current robot states. The force controller is derived from the computation model inspired by human motor learning principles [5]. The control variables in the controller, i.e., impedance and feedforward terms, are simultaneously adapted online and combined to generate the force/torque commands that are subsequently sent to the robot hand in the joint space. We validate our approach in several task scenarios, as shown in Fig. 2. See more results at `https://www.youtube.com/watch?v=xL9BvPGIKxE`.

This work was supported jointly by DFG and NSFC in project DEXMAN under grant No.410916101, and in TRR-169 Cross Modal Learning. Authors are with the TAMS group (Technical Aspects of Multimodal Systems), Department of Informatics, Universitat Hamburg, Germany.

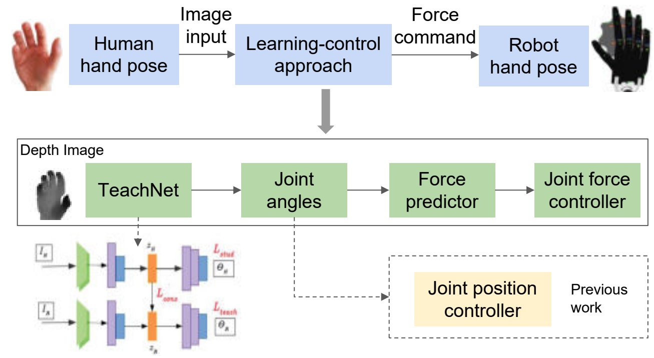
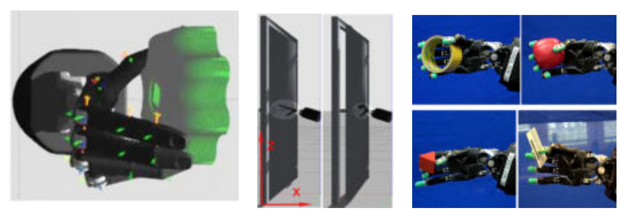


Fig. 1: The pipeline of the proposed learning-control approach [3].



(a) (b) (c)

Fig. 2: Selected task scenarios; (a) turning-a-cap; (b) opening-a-door; and (b) grasping.

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Learning Robust Mobile Manipulation for Household Tasks

Snehal Jauhri[1], Jan Peters[2], and Georgia Chalvatzaki[1]

***Abstract*— Intelligent robotic assistants should be able to perform a large variety of tasks in unstructured domestic environments. Mobile manipulation (MM) robots are an emblematic example of embodied agents, that can combine mobility, manipulability and multisensorial perception, to alter their environment for achieving the end-tasks. However, their autonomous execution is hindered by the major challenges in the combination of perception, planning and control. In this thesis, we investigate learning-based approaches for classical robotics with multimodal perception to achieve robust MM behavior. In one approach, we propose using deep reinforcement learning to intelligently move the base of the robot to maximize task success, e.g., for object fetching. To speed up exploration and ensure safety, we provide the kinematic reachability of the robot as prior information to the learning agent.**

Preferred type of presentation: Poster

I. Motivation and Problem Definition

Robots are expected to soon leave their factory/laboratory enclosures and operate autonomously in everyday environments, such as households (Fig. 1). However, operating in these environments is challenging, due to the unstructured nature of the real-world, and the large variety of tasks that need to be executed. Mobile manipulators are key in such scenarios, since they have the ability to perceive, as well as act, in the whole environment. Moreover, learning from prior experience is essential, since it can enable generalization to the diverse scenarios the robots will face. In this thesis, we propose coupling learning-based approaches with perception and control to learn robust MM skills.

II. Related Work

MM requires effective combination of methodologies from all aspects of robotics such as perception, motion generation, grasping, and control [1]. MM also needs good coordination between the different embodiments. Classic approaches such as [2] decouple arm/base motion, and first choose a base location using the kinematic reachability/manipulability of the robot arm, and then perform manipulation. The base-space that guarantees reachability is called the robot's inverse reachability. In [3], the inverse reachability constraint is treated as an obstacle avoidance problem. A reinforcement learning (RL) method is proposed in [4] to train an agent to move its base, while being rewarded for ensuring kinematic feasibility of the end-effector's motion. A hierarchical approach [5] uses a high-level RL policy that predicts base/arm sub-goals for a low-level motion generator to execute.

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[1]Intelligent Robotic Systems for Assistance group, Technische Universität Darmstadt, Germany {snehal,georgia}@robot-learning.de).

[2]Intelligent Autonomous Systems, Technische Universität Darmstadt, Germany mail@jan-peters.net).

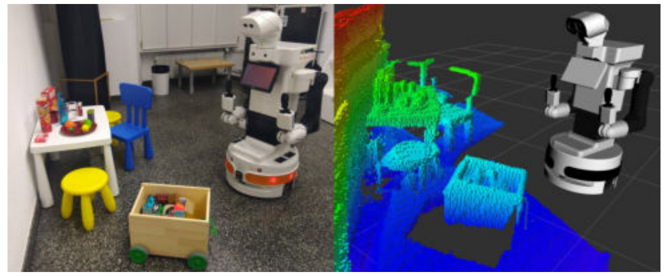

Fig. 1. A Tiago++ MM robot in a house-like environment

III. Own Approach and Contribution

In this thesis, we investigate modern machine learning techniques to solve perception and control problems in mobile manipulation. Classical robotics methods provide very useful priors that can be used in conjunction with learning. We elaborate on one such approach of ours for intelligent base placement. Prior methods for base placement [2], [3], [4] promise high reachability/manipulability, but do not consider the robot's actual task success. Moreover, these methods either do not consider or assume prior knowledge about obstacles or clutter in the environment. In [5], task success is used to train the RL agent and obstacle observations are considered. However, results only exist in simulation for simple tasks such as reaching and pushing (with a significant degree of reward shaping).

We propose learning a value function over base positions using task success (e.g., grasping success for a pick and place task) as reward. Moreover, the pre-computed inverse reachability of the robot is used as a prior to guide the learning. The prior can serve as an additional intrinsic reward and an exploration bias. We call this learned function a Spatial Value-based Mobile Manipulability Map. Obstacles and clutter in the environment are also considered by conditioning the learning on the observed occupancy map of the environment. In this way, optimal base placement for any MM task can be achieved.

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Achieving Robustness in a Drawer Manipulation Task by using High-level Feedback instead of Planning

Manuel Baum and Oliver Brock

***Abstract*— Robotic manipulation behavior should be robust to disturbances that violate high-level task-structure. Such robustness can be achieved by constantly monitoring the environment to observe the discrete high-level state of the task. This is possible because different phases of a task are characterized by different sensor patterns and by monitoring these patterns a robot can decide which controllers to execute. This eliminates the need to plan a temporal sequence of those controllers and makes the behavior robust to unforeseen disturbances. We implement this idea as a probabilistic filter over discrete states where each state directly activates a controller. Based on this framework we present a robotic system that is able to robustly open a drawer and grasp tennis balls from it.**

Preferred typ of presentation: Oral

I. Motivation and Problem Definition

Planning makes assumptions about the temporal evolution of the world when robots act in it. It creates a *model* of the world over future time-spans, but such models may be invalidated by the numerous unforeseen real-world contingencies. Instead of relying on such model predictions, we argue it is better to follow the idea that "the world is its own best model" [1]. Why should we try to predict the world state and make decisions based on anticipated contingencies when we can instead simply react to the state of the world in the moment the contingencies actually occur?

II. Related Work

Classical planning approaches assume a determinstic world and explicitly predict its state after a linear sequence of robot actions. But linear plans likely fail when the world does not develop as expected. Contingent plans are more flexible, tree-like structures [2] that allow some robustness to unforeseen disturbances, but still only consider a limited set of temporal evolutions and fail if actual contingencies were not predicted. The idea of reactive planning is to avoid such predictions and instead act based on the environment's state [3]. Recently Robust Logical-Dynamical Systems[4] showed behavior with remarkable robustness to disturbances by constantly estimating the world state. But do we really need logical-geometric state-estimation?

III. Own Approach and Contribution

The purpose of state estimation is to extract information from sensor input that is sufficient to choose appropriate actions in the current context. If we use feedback controllers that can directly solve all sub-problems of a task, then for certain manipulation tasks the only state estimate we need is to identify which controller to activate. For such problems we can avoid complex logical-geometric state-estimation.

Fig. 1. A person holds a drawer shut while a robot tries to open it. Irrespective of such disturbances the robot can reliably open the drawer.

We present a method that can be used in complex manipulation tasks like opening a drawer and grasping tennis balls from it. It is based on an HMM which filters the discrete high-level state of the task and activates feedback controllers based on that state. It does not rely on a pre-defined sequence of controllers and does not implement prior knowledge about such a sequence as the HMM's state transition matrix is almost a diagonal matrix with a small uniform off-diagonal term. Yet the system is able to create complex interactions with the environment such as loops to re-establish lost grasps on the drawer handle or to re-grasp tennis balls when they fell out of the hand. By use of high-level feedback the system so robust that it can detect [5] and recover from significant interferences such as forcefully removing the end-effector from the handle during a successful grasp, holding the drawer shut during attempts to open it and randomly poking at the end-effector. The system recovers from such interferences even without explicitly programmed recovery behaviors.

Both authors are with the Robotics and Biology Laboratory, Technische Universität Berlin, Germany and the Cluster of Excellence "Science of Intelligence" (SCIoI). Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy - EXC 2002/1 "Science of Intelligence" - project number 390523135.

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A Dataset for Learning Bimanual Task Models from Human Observation

Franziska Krebs*, Andre Meixner*, Isabel Patzer and Tamim Asfour

***Abstract*— Learning semantics models of bimanual manipulation tasks from human demonstration requires capturing human body motion as well as the motion of all objects involved in the task. In this work, we present a new multi-modal dataset of bimanual manipulation actions with a large amount of variations containing accurate human whole-body motions, full configuration of both hands and the 6D pose of all objects.**

I. Motivation and Problem Definition

To effectively assist in households, robots need a wide set of bimanual skills, the ability to adapt to new, changing environments and to learn new skills. Learning from human demonstration is a promising approach to teach robots new skills in an intuitive and effective way. Our goal is to learn bimanual task models from human demonstration. Such task model should represent 1) symbolic information of the task, such as objects, actions, spatial and temporal relations between hands and objects, and 2) subsymbolic, sensorimotor information, such as human and object trajectories, forces, etc. In this paper, we present a multi-model dataset that provides a basis for learning task model of bimanual manipulation.

II. Related Work

In previous work various human motion databases and datasets were published, and range from single video recordings, multi-view and multi-modal data to motion capture recordings. We consider the multimodal capturing and large variations of human body and hand movements as well as objects involved in a bimanual manipulation task to be particularly relevant to this work. The *CMU-MMAC* database [1] provides bimanual cooking and food preparation tasks, but without explicitly tracking objects and hand configuration. *DIM* [2] focuses on interactive manipulation of tracked objects and tools, yet primarily involves unimanual actions and their variation. In contrast, the *GRAB* dataset [3] provides full 3D human shape and pose sequences during bimanual grasping and the execution of some actions including the motion of the face, both hands and the primary object.

III. Own Approach and Contribution

We present a new multi-modal dataset, published recently in [5], consisting of 12 bimanual actions of daily household activities performed by two subjects with a large number of intra- and inter-action variations. The data is collected using five different sensor modalities: i) optical motion capture system to record accurate whole-body human and object motion, ii) two data gloves that provide finger joint trajectories, iii) three RGB-D cameras recording from an observer perspective, iv) a head-mounted egocentric camera and v) three inertial measurement units attached to the human body. An excerpt of the motion recordings is presented in Figure 1. We extended the Master Motor Map (MMM) framework [4] to offer methods for multi-modal data processing and include an individual action segmentation and annotation for each hand. The dataset is publicly available as part of the KIT Whole-Body Human Motion Database[1].

Fig. 1. Eight bimanual manipulation action recordings from this dataset mapped to the MMM reference model [4]

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* The first two authors contributed equally to this work.

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[2]The authors are with the Institute for Anthropomatics and Robotics, Karlsruhe Institute of Technology, Germany {franziska.krebs, andre.meixner,isabel.patzer,asfour}@kit.edu

[1]https://motion-database.humanoids.kit.edu/

EMG-driven Machine Learning Control of a Soft Glove for Grasping Assistance and Rehabilitation

Marek Sierotowicz[1†], Nicola Lotti[2†*], Francesco Missiroli[2], Ryan Alicea[2], Michele Xiloyannis[3]
Claudio Castellini[1] and Lorenzo Masia[2]

Abstract— **In the field of rehabilitation robotics, transparent, precise, and intuitive control of hand exoskeletons still represents a substantial challenge. In particular, the use of compliant systems often leads to a trade-off between lightness and material flexibility, and control precision. In this work, we present a compliant, actuated glove with a control scheme to detect the user's motion intent, which is estimated by a machine learning algorithm based on muscle activity. Six healthy study participants used the glove in three assistance conditions during a force reaching task. The results suggest that active assistance from the glove can aid the user, reducing the muscular activity needed to attain a medium-high grasp force and that closed-loop control of a compliant assistive glove can successfully be implemented by means of a machine learning algorithm.**

Preferred typ of presentation: Poster

Keywords: Wearable robotics, Machine learning, Soft robotics

I. Motivation and Problem Definition

Neuromuscular diseases and traumatic events impair manipulation skills with a significant incidence rates, dramatically worsening the quality of life for affected people. However, wearable robotics entered the stage to help people with motor impairments in restoring or compensating for lost motor functions : in particular, the introduction of soft materials in these actuated devices enhanced the human-machine interaction with promising results in the rehabilitation realm.

II. Related Work

Most of the soft actuated gloves present in literature are controlled based on intent detection algorithms, but many aspects are still challenging: the most common approach is based on motor synergy analysis, which can simplify the otherwise prohibitively complex mapping of muscle activity to primary postural tasks [1]. This is done by identifying specific patterns in brain activity [2] or neuromuscular signals [3]. The latter approach has been further developed whit an open-loop sEMG logic classified gross muscle contractions responsible for flexion and extension and fed the information to a low-level fluid pressure controller which regulated the pressure simultaneously in all actuators of a pre-selected group. [4].

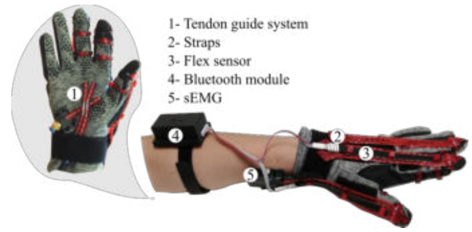

Fig. 1. *MyoGlove design.* The presented prototype actively assists hand grasping by means of tendon-driven actuators (1), while opening is passively aided by three 3D printed elastic straps (2). Hand movements are sensed by means of two flex sensors measuring overall thumb and index flexion/extension (3-4). The motion intent is estimated by means of sEMG (5).

III. Own Approach and Contribution

Our work aims to combine, for the first time, a soft wearable glove with a user's motion intent detection based on machine learning approaches enrolled in a closed-loop control. The device is characterized by means of a rehabilitative apparatus that includes a haptic handle device for grasping training. We investigate, by comparing two different machine learning algorithms, the kinematic and physiological effects of the glove in a cohort of six healthy users, in a repeated-measures study design consisted in a force reaching task. The results provide initial indicators for the usability of this apparatus in rehabilitation for task-oriented restorative training.

† M. Sierotowicz and N. Lotti equally contributed to this work.

[1]M. Sierotowicz and C. Castellini are with the Institute of Robotics and Mechatronics, German Aerospace Center (DLR), 82234 Wessling, Germany and with the Department of Artificial Intelligence in Biomedical Engineering (AIBE), Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91052 Erlangen, Germany.

[2]N. Lotti, F. Missiroli, R. Alicea and L. Masia are with the Institute for Technical Informatics (ZITI), Heidelberg University, 69120 Heidelberg, Germany.

[3]M. Xiloyannis is with the Institute of Robotics and Intelligent Systems, ETH Zürich, Zürich, 8092, Switzerland.

* corresponding author, nicola.lotti@ziti.uni-heidelberg.de

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Interconnected Recursive Filters in Artificial and Biological Vision

Aravind Battaje and Oliver Brock

***Abstract*— We aim to find fundamental characteristics of robust vision and express them as interconnected recursive filters, which is a network capable of feed-forward and feedback information. We demonstrate that certain visual illusions can be explained using interconnected recursive filters, while also serving as an algorithmic architecture to build robotic vision applications.**

Preferred type of presentation: Oral

I. Motivation and Problem Definition

Today's artificial vision is hardly as versatile as biological vision. Artificial vision works really well in human-designed niches, but are not robust in general situations. This hinders producing intelligent robotic solutions for day-to-day tasks. To achieve similar performance as biological vision then, one way is to identify the fundamental differences and import the qualities necessary for robust vision. However on the one hand, those qualities are not well known, and on the other, such qualities may not be easily expressible for artificial vision.

II. Related Work

Historically there have been many attempts to mimic neural mechanisms for machine vision. The most prominent work [1] in deep-learning cemented CNNs into common usage, but it still deviates in crucial ways from biological vision. For example, it is well known that information flows top-down and bottom-up in the visual cortex [2]. We believe CNNs are insufficient and fragile [3], and also don't allow mechanisms that are necessary for robust vision.

III. Own Approach and Contribution

Some important characteristics that have been identified in biological vision, but not fully leveraged yet in artificial vision are: multi-directional information flow [2], crossmodal fusion between different aspects of sensory information [4] and temporal coherence [5]. We believe interconnected recursive filters provide a language to express these qualities in a holistic way, because it is composed of a network of recursive (Bayes) filters that allow probabilistic fusion of multiple information sources while associating multiple priors (such as time consistency). Martín-Martín et al. [6] have already applied this to a robotic problem to detect and track kinematic degrees-of-freedom of arbitrary objects.

Both authors are with the Robotics and Biology Laboratory, Technische Universität Berlin, Germany and the Cluster of Excellence "Science of Intelligence" (SCIoI). Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy - EXC 2002/1 "Science of Intelligence" - project number 390523135.

Given that we have a framework to express qualities necessary for robust vision, we follow an iterative strategy to accelerate our process: From hypotheses about certain characteristics of human vision, we build synthetic models using interconnected filters to verify those hypotheses. With the deviations and insights from such modeling, we perform psychophysical experiments on humans, which in turn reveals new strategies to model. Since we use interconnected filters during the process, it can easily transfer to robotic applications as demonstrated by [6].

We attempt such an iterative strategy to understand mechanisms in human vision related to shapes and color: We emulate two illusions using interconnected recursive filters, viz., "Filling-in afterimage between the lines" [7] elicits illusory colors in shapes as an aftereffect, and "neon-color spreading" [8] bleeds colors confined to contours of a shape. We explain such illusions by a constraint that arises from tightly coupling shape and color perception. Some may regard these illusions as glitches in human vision, but we believe this can be seen as taking advantage of statistics of natural image sequences [9]. We have still not completed a full verification with psychophysical experiments, but literature [9] already supports our view.

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Distributed Semantic Mapping for Heterogeneous Robotic Teams

Yunis Fanger[1], Tim Bodenmüller [1], and Rudolph Triebel[1]

Abstract— **In this paper we summarize our current work on distributed semantic mapping within heterogeneous robot teams in large scale unstructured environments. We extract semantic information from sensor readings and use it to perform robust registration of sub-maps from different agents. We further use it to reduce network traffic by excluding detected areas of high uncertainty. For fast development and verification of our approaches, we employ a multi-robot real-time simulation.**

Preferred type of presentation: Poster

I. Motivation and Problem Definition

We consider the problem of generating accurate and efficient 2D or 3D map representations with a distributed team of heterogeneous mobile robots. While such a robot team can produce environment maps much more efficiently than single robot systems, there are also a number of additional challenges. These include the requirement to keep the individual maps consistent due to the lack of a centralized map, the ability to identify map elements that have been recorded from different view points, and the problem of fusing map data from different sensor modalities with different resolutions. In our work, we propose to leverage semantic information in addition to the geometric data to tackle these problems. More precisely, we propose to use terrain and object classification methods to find correspondences in the maps (see Sec. III) while limiting the communication load within the team.

II. Related Work

Simultaneous localization and mapping (SLAM) has been extensively researched and implementations such as ORB-SLAM [1] were developed which work well in static environments. More recently, researchers have started to exploit the progress made in the field of semantic image segmentation [2] in order to improve SLAM approaches. In [3] and [4] extensions to ORB-SLAM are presented which filter out feature points if their semantic label indicate them to belong to dynamic objects. However, in both these works only the most likely semantic label are considered. In [5] a distributed semantic SLAM approach is proposed that takes into account how the viewpoint of different robots affects their ability to accurately assign objects to semantic classes. However, the issue of how to perform data association is not addressed here. It has also been shown [6] that considering semantic labels when aligning point clouds using the well known the IPC algorithm yields improved results. Finally, authors in [7] provide a conceptional framework for creating modular software for distributed semantic mapping systems.

[1]Institute of Robotics and Mechatronics, German Aerospace Center(DLR), Germany

III. Own Approach and Contribution

In our work we propose the incorporation of semantic information in the map building process of our heterogeneous multi-robot team consisting of two lightweight rover units [8] and a quadrocopter. For the application case of extraterrestrial exploration the semantics are considered to be information about different rock and terrain types found in the environment, while for scenarios on earth additional semantic labels for objects such as trees, water, and foliage are possible. In a first step we use pixelwise semantically segmented RGBD-camera images [2] to incrementally build a local map of a robots surroundings. Taking multiple measurements of a single location in the environments from different points of view enables us to generate a distribution over semantic labels from the discrete classification in the segmented images. The semantic local maps are then used for multi-robot map registration. However, instead of sending the entire local map to other robots, we propose to only communicate the subset that contributes most to accurate map matching. Thus, the parts of the map that have a semantic class that hints on dynamic elements or high uncertainty are excluded. When a robot receives a new partial sub-map from one of its team members a map matching procedure is triggered. Hereby, possibly matching sub-maps are first selected according to current pose estimates and then precisely aligned, by utilizing the semantic labeling. In contrast to other approaches we consider not only the most likely semantic class for each point in the map but rather the entire probability distribution by weighting points accordingly in a final semantic IPC step. For fast development and testing, we implemented a simulation that generates sensor readings and semantic labels in real-time from photo-realistic virtual extraterrestrial and large scale outdoor environments.

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A Dexterous Hand-Arm Teleoperation System based on Hand Pose Estimation and Active Vision

Shuang Li[1], Norman Hendrich[1] and Jianwei Zhang[1]

***Abstract*— In this paper, we develop a novel vision-based hand-arm teleoperation system that maintains the human hands captured from the best viewpoint and at a suitable distance. This teleoperation system consists of an end-to-end hand pose regression network and a controlled active vision system. Quantitative network evaluation and a variety of complex manipulation tasks demonstrate the practicality and stability of the proposed teleoperation system.**

Preferred type of presentation: Oral

I. Motivation

Markerless vision-based teleoperation offers the advantages of allowing for natural, unrestricted limb motions and of being less invasive [1]. Especially markerless methods are suited to dexterous teleoperation, which requires capturing all the essence of finger motions. However, these vision-based pose estimation algorithms still suffer inaccuracy issues due to the self-occlusion of the fingers. Therefore, we devise a markerless vision-based hand-arm teleoperation system in conjunction with an end-to-end hand pose estimation method, Transteleop, and a real-time active vision system.

II. Related Work

Many markerless vision-based teleoperation approaches separately research the visual perception of human bodies (*e.g.* human hand pose estimation) and the robot control (*e.g.* kinematic retargeting) [2]. To improve the efficiency and intuitiveness of the teleoperation system, instead of the two-stage visual teleoperation, Li *et al.* [3] presented an end-to-end network to exploits the geometrical resemblance between human hands and the robot hand. To solve the limited viewpoint problem in hand pose estimation methods, active vision is a good option that keep the camera captureing the human hand from the best viewpoint and at an optimal distance. The common form of an active vision system is that the vision sensor is either mounted on the end effector of a manipulator as a hand-eye system or Pan-Tilt robots [4].

III. Approach and Contribution

A. Tranteleop

Transteleop is a novel vision-based deep learning model, which is inspired by image-to-image translation methods. Transteleop observes the human hand through a low-cost depth camera and generates not only joint angles but also depth images of paired robot hand poses. Except for a joint angle loss, a keypoint-based reconstruction loss is exploited to explore the resemblance in appearance and anatomy between human and robotic hands and enriches the local features of reconstructed images.

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[1]All authors are with Group TAMS, Dept. of Informatics, Universität Hamburg. {firstname.lastname}@uni-hamburg.de

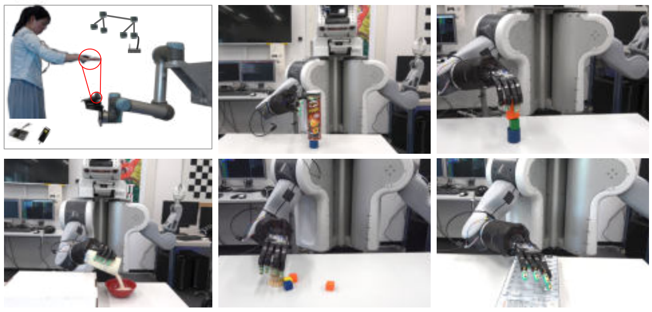

Fig. 1. The first image in the first row shows the user state in the local site. The other five images are the screenshots of the robot experiments, *i.e.*, pick and place, tower building, pouring, sweeping, and midi mixer fader sliding.

B. Controlled Active Vision System

The real-time active vision system allows the camera to capture the human right hand at optimal viewpoints by involving a moving vision sensor. The vision sensor is mounted on the end-effector of the robot arm. Such a tracking system should ensure that: 1) the robot smoothly follows the human hand in real-time; 2) the robot keeps a safe distance from the human; 3) the robot arm satisfies the required workspace of manipulation tasks. To achieve these requirements, a real-time trajectory generation method, collision checking and workspace analysis were conducted.

We prove the reliability and practicality of the proposed teleoperation system by the network evaluation, trajectory analysis and non-trivial robot experiments across two trained demonstrators (see Fig. 1).

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Multimodal Perception for Robotic Pouring

Hongzhuo Liang[1], Norman Hendrich[1] and Jianwei Zhang[1]

Abstract— **Robust and accurate estimation of liquid height lies as an essential part of pouring tasks for service robots. However, vision-based methods often fail in occluded conditions, while audio-based methods cannot work well in a noisy environment. We instead propose a multimodal pouring network (MP-Net) that is able to robustly predict liquid height by conditioning on both audition and haptics input. We also augment the audio data by inserting robot noise. Both network training results and robot experiments demonstrate that MP-Net is robust against noise and changes to the task and environment.**

Preferred type of presentation: Oral

I. Motivation

Pouring a specific amount of liquid into a container is a challenging manipulation skill for service robots. However, humans can infer whether the target container is almost full from the pouring sound and use their proprioceptive haptic feedback to estimate how much liquid is poured out from the source container. Inspired by human experiences, we propose to tackle the issues of robust robotic pouring by a multimodal perception method (See Fig 1).

II. Related Work

For the robust and accurate perception of robot pouring, recent approaches mainly rely on vision [1]. However, vision fails under occlusions or in the dark. Using audio is a second option for robot pouring perception, but the performance of this method will degrade in a noisy environment [2]. If the robot is equipped with force/torque sensing, the liquid height in a target container can only be predicted if the initial fill level and the shape of the container are known [3]. Recent studies have shown that multimodal sources represent the environmental features better than single modality in pouring tasks [4]. Wilson *et al.* [5] implemented a multimodal convolutional neural network, which fuses audio and visual data, to predict the weight of the poured liquid, detect overflow, and classify the liquid and the target container.

III. Own Approach and Contribution

We propose a multimodal pouring network [6] that can robustly predict liquid height by conditioning on both audition and haptics input. The pouring process is a typical sequential problem, and the predicted length has a temporal relationship. Intuitively, we choose a recurrent network as our model architecture. We augment audio clips with noise and transform them into audio spectrograms using Short-Time Fourier Transform (STFT). The raw haptic data within the same period is concatenated with the audio data as inputs. Then each time slice of the fusion data is progressively fed into the recurrent unit.

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[1]All authors are with the TAMS Group, Dept. of Informatics, Universität Hamburg. {firstname.lastname}@uni-hamburg.de

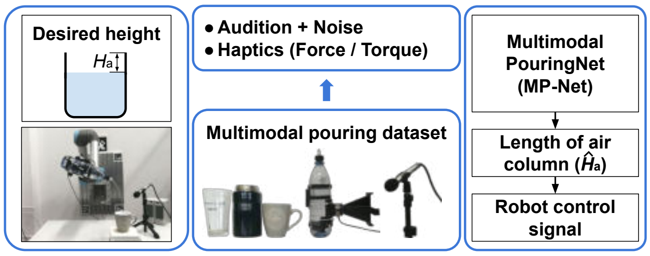

Fig. 1. The proposed multimodal pouring pipeline. By giving the audio and haptic as input, our Multimodal PouringNet (MP-Net) predicts H_a as output. This output is then used to control the robotic pouring.

Due to the fact that when the length of the air column gets shorter in an organ pipe, the air vibrates faster and the resonance frequency of the air increases, it is more indicative of choosing the length of the air column H_a as the ground truth of our model instead of the liquid height. MP-Net is trained on a self-collected multimodal pouring dataset, which contains 300 robot pouring recordings with audio and force/torque measurements for three types of target containers.

The multimodal perception system is systematically tested across four baselines and a wide range of robotic pouring experiments in a noisy environment. The results substantiate that MP-Net is quite robust against noise and against changes in different tasks and varying environments. Moreover, the multimodal nature of our network lets us reconstruct the shape of the target container.

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Physically Plausible Tracking and Reconstruction of Dynamic Objects

Michael Strecke[1,2] and Joerg Stueckler[1]

***Abstract*— In order to safely navigate in and interact with their environment, robots require knowledge about the positions and movements of objects in their surroundings. Spurred by the wide availability of relatively cheap sensors, simultaneous localization and mapping (SLAM) from RGB-D (color and depth) video has become a popular method for scene reconstruction and localization. While most previous methods assume static scenes or disregard dynamic objects as outliers, we present a novel approach for tracking and reconstructing multiple dynamic objects. We furthermore present a novel method that uses physical plausibility priors for shape completion.**

Preferred type of presentation: Oral

Keywords: object tracking, shape reconstruction, shape completion

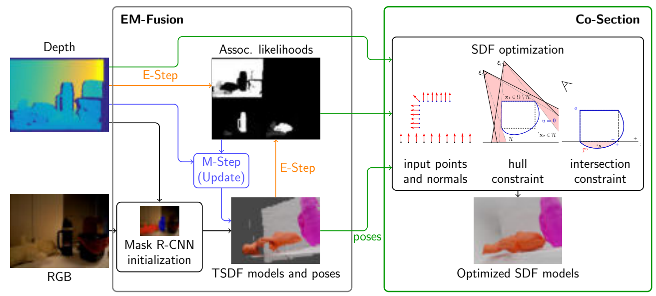

Fig. 1. Overview of our approach. EM-Fusion tracks and maps objects in a probabilistic fashion. Co-Section uses input points (computed from depth maps) together with hull and intersection constraints to optimize completed shapes.

I. Motivation and Problem Definition

Our goal is to reconstruct objects and track their movements in dynamic scenes recorded in RGB-D videos to allow robots to safely navigate in and interact with their environment. We tackle two main challenges in the work presented here. 1) in dynamic scenes, changes in pixel values over time originate from movements of different objects, requiring association of pixels to objects for successful tracking and mapping [1]. 2) approaches like EM-Fusion [1] only map the visible part of the objects, while for interactions, like grasping of objects, at least a coarse estimate of the complete shape of the objects is required [2].

II. Related Work

With the wide availability of RGB-D cameras, SLAM based on this data has seen tremendous progress, yielding many approaches to tracking and mapping static scenes in real-time. Co-Fusion [3] is among the first methods to track dynamic objects in RGB-D videos. It provides a benchmark dataset for evaluating multi-object tracking performance.

In Co-Section [2], we build upon the Hessian-IMLS optimization approach from [4] for dense surface reconstruction.

III. Own Approach and Contribution

Fig. 1 shows an overview of our method. EM-Fusion [1] uses Mask R-CNN [5] to initialize object-wise truncated signed distance field (TSDF) models. The models are then tracked and mapped in a probabilistic fashion based on the expectation maximization (EM) algorithm. Our EM algorithm consists of two main steps. In the E-Step, pixel associations to object models are computed based on the distance of the respective models to the incoming depth frame. The M-Step then uses these association likelihoods to track and map the objects. Evaluation on the benchmark scenes from [3] shows improved tracking accuracy of our method compared to multiple comparison approaches.

Co-Section [2] is an extension to EM-Fusion [1] aiming at retrieving completed object models. It builds upon the tracking and mapping pipeline from EM-Fusion and extends it with global optimization [4] to get globally optimal signed distance fields (SDFs). Closure of object models is achieved by utilising physical plausibility priors present in dynamic scenes that lead to hull and intersection constraints

Acknowledgment

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[1]Embodied Vision Group, Max Planck Institute for Intelligent Systems, Tübingen, Germany. E-Mail: firstname.lastname@tue.mpg.de.

[2]3rd-year PhD student, Supervisor: Joerg Stueckler.

Detecting Robotic Failures Using Visual Anomaly Detection

Santosh Thoduka[1] and Juergen Gall[2] and Paul G. Plöger[1]

Abstract— **Detection of task failures is required for robots to be resilient to inevitable failures. We approach task failure detection using visual anomaly detection, by modelling nominal camera motion, robot body motion and scene motions using a combined analytical and learning method. We also collect video datasets of failed and successful executions of different robotics tasks, such as object placement and object handover.**

Preferred type of presentation: Oral

I. Motivation and Problem Definition

Task failures in autonomous robots cannot be completely eliminated, especially when the task involves interacting with unstructured environments or people. Consequently, we expect robots to be resilient to failures by detecting when the occur and performing actions to correct them. Considering a placement action, the robot may place the object in an unstable configuration, causing it to fall off the surface. In this, and other similar tasks, the robot typically perceives the scene with a camera, providing the opportunity to visually detect such failures. Failures can occur in often unpredictable ways, making it impossible to enumerate all types of failures. This leads us to formulate failure detection as an anomaly detection problem, as has been done in previous work [1], [2], rather than a classification problem. Therefore, in this work we focus on detecting failures in robotic task execution using visual anomaly detection.

II. Related Work

In robotics, failure detection has been approached in several ways including *(i)* using anomaly detection during a feeding task using force, sound and vision modalities [1]; *(ii)* classification of action executions into success and failure using HMMs and end-to-end CNNs [3]; and *(iii)* slip and grasp failure detection using vision and tactile sensors [4], [5]. These methods are typically characterised by the use of learning from multi-modal data using neural networks or hidden Markov models. Multiple sensors, including cameras and proprioceptive sensors are used; however video-based anomaly detection methods have not been sufficiently explored for this problem.

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[1]Santosh Thoduka is a PhD student of 3 years supervised by Professors Juergen Gall and Paul G. Plöger. Santosh Thoduka and Paul G. Plöger are with the Computer Science department, Hochschule Bonn-Rhein-Sieg, Sankt Augustin 53757, Germany `santosh.thoduka, paul.ploeger@h-brs.de`

[2]Juergen Gall is with the Computer Vision department, University of Bonn, Bonn 53111, Germany `gall@iai.uni-bonn.de`

III. Own Approach and Contribution

While the focus of our approach is applying video-based anomaly detection in robotics, we also aim to make use of known robot commands, additional sensors and task knowledge. The current state of the art methods in video anomaly detection use autoencoder networks that learn to reconstruct nominal inputs. Since they are trained only on nominal data, poorly reconstructed outputs are detected as anomalies. In [6], we propose modelling nominal *motions* as seen from the robot's camera during task execution. Three types of motions are modelled separately, namely, the motion of the robot's own camera, motion of the robot's body and all other scene motions. The first two are modeled analytically using the robot's kinematics and 3D model, whereas an autoencoder network is used to learn to predict nominal scene motions given past motions. The combined learning and analytical approach shows improved performance compared to using learning alone. The dataset that we evaluated our approach on consists of videos of our robot placing books on a shelf, which included anomalous events such as the book falling off the shelf, other books being disturbed, the camera being occluded and the robot being disturbed.

As part of the METRICS project[1], we also collected a dataset of videos of robot-to-human and human-to-robot handovers, in which trials included the person dropping objects, ignoring the robot, and not releasing the object. These datasets are relatively small compared to large-scale video datasets. Therefore, on-going work includes the creation of larger datasets with various robots.

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[1]`https://metricsproject.eu/`

Skill Generalisation and Experience Acquisition for Predicting and Avoiding Execution Failures

Alex Mitrevski†, Paul G. Plöger†, and Gerhard Lakemeyer‡

***Abstract*— For being flexible and reliable in everyday environments, autonomous robots need introspective capabilities that allow them to analyse failures experienced during execution. Execution failures are, however, rarely dealt with explicitly in existing work, or the problem is mitigated by using rich policy representations, but which make it difficult to perform failure analysis. Our work studies robot execution failures, particularly those that arise by the need for generalising execution knowledge to varied contexts. We particularly work towards developing methods that make it possible to execute skills reliably, but which also enable explicit failure analysis when execution failures do occur.**

Preferred type of presentation: Oral

I. Motivation and Problem Definition

The process of robot action execution is associated with uncertainty and, as a result, a possibility of experiencing execution failures. An intelligent autonomous robot should be able to analyse the causes of failures so that it can address them effectively, but also so that it can provide failure explanations when necessary. This, in turn, requires a skill representation that allows such analysis to be performed. In our work, we are interested in (i) identifying criteria that affect the possibility of analysing robot execution failures and (ii) developing execution techniques that allow predicting and diagnosing failures as well as learning from them.

II. Related Work

In traditional fault detection and diagnosis, the assumption is that faults are caused by broken (hardware or software) components; the diagnosis objective is finding components that are likely fault candidates [1], [2]. Execution failures may, however, also be caused by insufficient or inappropriate execution knowledge, or due to external influences, not only broken components. Methods that deal with one class of execution failures – those that result from inappropriate planning preconditions – are proposed in [3]; however, the naive physics technique there requires extensive knowledge engineering, while the simulation-based method does not produce generalisable representations. Indirectly, the problem of execution failures is also dealt with via flexible execution policies, often acquired using reinforcement learning [4], but such policies are generally difficult to analyse explicitly due to the complexity of the underlying representation.

III. Own Approach and Contribution

In [5], we discussed a hybrid model of parameterised execution skills, which combines qualitative execution preconditions with a continuous success prediction model, possibly under multiple qualitative execution modes. This representation is based on an analysis of existing policy representations in terms of their diagnosability [6]. Using this model, we showed that execution failures can be analysed as violations of the qualitative preconditions; the failed action parameters can subsequently be corrected by consulting both the qualitative and the continuous model [7]. In [8], we embedded this representation in a framework that biases generalisation between object classes using an object ontology, but also incorporates a robot's own generalisation experiences to improve the generalisation outcomes. Additionally, our work has looked into verifying the execution of skills in simulation via success properties [9] and into adapting skills to different action contexts [10], such that we aim to embed our hybrid model in these scenarios as well.

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*Alex Mitrevski is currently a PhD student

†Alex Mitrevski and Paul G. Plöger are with the Department of Computer Science, Hochschule Bonn-Rhein-Sieg, Sankt Augustin, Germany <aleksandar.mitrevski, paul.ploeger>@h-brs.de

‡Gerhard Lakemeyer is with the Department of Computer Science, RWTH Aachen University, Aachen, Germany gerhard@informatik.rwth-aachen.de

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Improving HRI through robot architecture transparency[3]

Lukas Hindemith[1,2], Anna-Lisa Vollmer[1] and Britta Wrede[1]

Abstract— **In recent years, an increased effort has been invested in improving the capabilities of robots. Nevertheless, human-robot interaction remains a complex field of application where errors occur frequently. In this work, we investigate ways to improve users' understanding of robots. For this, we employed a legible behavior-based control architecture and conducted an online simulation user study to evaluate two complementary approaches to convey and increase the knowledge about this architecture to non-expert users.**

Preferred type of presentation: Oral
Keywords: explainable robots, mental models, control architecture

I. Motivation and Problem Definition

Advancements in robot capabilities have facilitated the transition of application fields from mainly industrial to private environments. Therefore, interaction partners are no longer primarily experts but also lay users. Although robots are capable of interacting with naive users in general, problems occur regularly. Besides hardware and software failures of the robot, users induce errors through mistakes. These mistakes can be primarily ascribed to the lack of knowledge about the capabilities and limitations of the robot [1]. With the robot control system at the core of each human-robot interaction, it is of utmost importance that users comprehend the decision-making process of robots. To tackle this problem, we employed a legible robot control architecture with (a) a visualization and (b) a visual programming interface to improve human-robot interactions. The resulting comprehensibility about the architecture based on these two approaches was evaluated in a simulation online user study.

II. Related Work

When interacting with a robot, it is important for the user to comprehend the course of the interaction [2]. In many instances, particular actions are only understandable if the overarching goal is known. Therefore, a robot should not only communicate which action it executes but also what underlying goal should be achieved with it [3].

Various architectures for robot control use complex control structures to achieve goal-oriented behavior. While these allow for solving challenging tasks, the comprehension by naive users suffers. This is primarily due to the frequently used hierarchical structure of the planning process [4]. In contrast, behavior-based controls are more reactive in their traditional form, which improves comprehension [5]. Therefore, we utilize a behavior-based approach for increased comprehensibility.

III. Own Approach and Contribution

Our behavior-based robot control architecture aims to provide an easy-to-understand reasoning process. Therefore, no highly mathematical planning component was utilized.

We developed two complementary approaches to improve naive users' understanding of the robot's decision-making process. A visualization of the architecture was developed to make the inner processes legible for users. Besides static visualizations about the components, the first approach included dynamic visualizations to improve the comprehensibility of the inner processes. The second approach was a visual programming interface, where users defined the behavior of the robot. Both approaches were evaluated in an interactive online simulation user study, with a 2-by-2 between subject study design. In this study, 81 participants were first taught about the architecture, then interacted with a simulated robot and were asked to achieve a joint goal. In the end, a questionnaire was administered to measure their knowledge about the architecture.

The analysis of the study revealed that an increase in knowledge about the architecture improved the interaction in terms of more successful interactions and fewer errors during the interaction. However, the dynamic visualization had no direct impact on users' knowledge. Additionally, the visual programming interface only improved knowledge about certain components of the architecture. Interestingly, a negative correlation between anthropomorphization and interaction success was observed. This result indicates that anthropomorphization impedes users' comprehension.

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[1]Authors are with CoR-Lab, CITEC and Medical School OWL, Bielefeld University, 33619 Bielefeld, Germany {lhindemith;avollmer;bwrede}@techfak.uni-bielefeld.de

[2] LH is a third year PhD candidate, supervised by BW and AV.

[3] Under review in the Frontiers in Robotics and AI Journal.

Improving safety in human-robot collaboration by using brain-computer interface technology

Jianzhi Lyu[1], Alexander Maye[2], Norman Hendrich[1], Andreas K. Engel[2] and Jianwei Zhang[1]

Abstract— **To avoid collisions and make collaboration in a shared workspace safe, robots need to detect the human's movement intention as early as possible, thus allowing for the time needed to replan and execute the robot's trajectory. In this paper, we present a setup for studying how information recorded from a motion-tracking system and the electroencephalogram (EEG) of the human brain can be exploited for dynamically adjusting the robot's trajectories. In particular, we employ a brain-computer interface (BCI) to detect the target of the human's overt attention and develop a controller which minimizes interference with the human's action yet maximizes performance in the robot's task. Moreover, EEG data are used to evaluate the operator's vigilance and adapt parameters of the robot movements accordingly.**

Preferred type of presentation: Poster

I. Motivation and Problem Definition

In a narrow shared work space, a challenging question is how to coordinate robot and human actions in a way that ensures fluency and safety of the collaboration. Two main approaches to this question are being investigated, i.e., reactive and predictive approaches. Most of the predictive approaches infer the human's intention from tracking body motion, gaze or brain activity. However, predicting human action is inherently unreliable and difficult even for humans. Therefore, the question arises of how a trajectory optimizer can use probabilistic information about movement intentions to guarantee human safety and task efficiency. Another question concerns the adaptation of the robot to the mental state of the human, e.g., for counteracting accidents caused by drowsiness.

II. Related Work

The existing work about human reaching target prediction can be divided into three categories. The fist category describes motion-based methods like [1]. One inherent problem of motion-based methods is that prediction is only possible after observing the human's movement for some time. The second category are gaze-based methods, e.g., [2]. The last category are BCI-based methods. One interesting approach here is to analyze the Bereitschaftspotential (readiness potential), which can detect movements up to 500 ms before onset [3]. This signal, however, provides no information about the target or the trajectory of the movement and hence cannot support the robot trajectory adaption.

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[1]Jianzhi Lyu, Norman Hendrich and Jianwei Zhang are with the Department of Informatics, Universität Hamburg, Hamburg, Germany{lyu, hendrich, zhang}@informatik.uni-hamburg.de

[2]Alexander Maye and Andreas K. Engel are with the Department of Neurophysiology and Pathophysiology, University Medical Center Hamburg-Eppendorf, Hamburg, Germany{a.maye, ak.engel}@uke.de

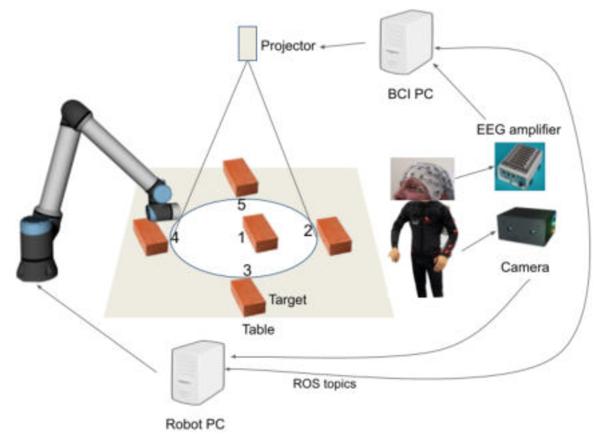

Fig. 1. Schematic of the platform for studying BCI-augmented HRC.

III. Own Approach and Contribution

Our approach rests on the observation that humans usually turn their focus of attention to the space where they are going to act; e.g., they frequently gaze at the location where they will grasp or place an object. To detect the focus of overt visual attention, we employ a spatially-coded SSVEP-BCI [4]. With the information about the target of the human's reaching movement, together with data from the initial movement phase recorded by a motion-tracking system, the online trajectory optimizer generates a goal-oriented and collision-free trajectory for the robot. In addition, EEG signatures of vigilance and alertness are used to modulate safety distance thresholds and speed limitations of the trajectory optimizer in an online fashion.

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Flexibility in Human-Robot Teams

Challenges and Solution Approaches

Dominik Riedelbauch[1]

Abstract— **Human-robot teaming attracts an ever-increasing level of attention in academia as well as in industry. Mixed teams promise enhanced productivity and job attractiveness to small and medium enterprises that are not suited for traditional, fenced automation solutions. Yet, coordinated task sharing among heterogeneous partners requires intelligent cobots that are capable of acting flexibly under the influence of process and product variety. This short paper summarizes facets and challenges of flexibility in human-robot teams together with our prior contributions and future research directions.**

Keywords: human-robot teaming, joint task coordination, task modelling, virtual commissioning

I. Motivation and Problem Definition

Partial automation in manufacturing enables enhanced productivity and job attractiveness, *e.g.* due to improved ergonomic conditions [1]. Particularly small and medium-sized enterprises can hardly benefit from traditional automation with statically programmed, fenced robots – setting up respective systems is often too effortful and inflexible when operating robots in unstructured environments, especially when they are strongly influenced by humans. We, therefore, envision an intelligent robot colleague capable of intuitively sharing work with humans in industrial tasks while adapting flexibly to a broad spectrum of product and process variance.

II. Related Work

Related work on human-robot task sharing can be split into static and dynamic approaches. *Static* methods rely on capability indicators assigned to each work item. These indicators quantify the fit of humans or robots to work items. Hence, they enable multi-criteria optimization to minimize makespans and maximize the alignment of task assignment with agent capabilities (*e.g.* [1], [2]). This leads to fixed schedules that humans and robots have to adhere to. By contrast, *dynamic* approaches offer more flexibility by online (re-)planning during joint task execution. Corresponding strategies including our own work (*e.g.* [3], [4]) have mostly focused on robot adaption to human decisions on the ordering of work items – product part variety as a consequence of mass customization, and robustness to human or robot error, changing part feeding locations *etc.* have played a minor role so far. Yet, mixed teams must also reflect these aspects to achieve the full range of flexibility that maximally reduces the hurdle to use robots as team members in production.

[1]Dr. Dominik Riedelbauch is a postdoctoral researcher at the Chair for Applied Computer Science III (Robotics and Embedded Systems) of Prof. Dr. Dominik Henrich, University of Bayreuth, 95447 Bayreuth, Germany `dominik.riedelbauch@uni-bayreuth.de`

III. Our Approach and Contributions

We are therefore contributing towards solving the below challenges linked to the design of flexible robot co-workers:

Task Modelling: Flexible robot use requires means for end-users to transfer knowledge on joint tasks to the system. Task-level visual programming has recently become broadly available. We have so far investigated the applicability of this paradigm to models for several agents with 'earlier-later'-relations between robot skills. Future work will integrate product variety management by allowing for partly under-specified skill parameters to be grounded at execution time.

Coordination: Once a shared task has been formulated, the division of work must be coordinated online. Our contribution is a heuristic approach that handles partial observability of task progress emerging from a cost-effective yet limited sensor setup. The team can switch between coexistence, cooperative parallel work, and collaboration with physical contact. Configurable state machines control the robot coordination behaviour in terms of action, active perception, and human-robot communication. The approach puts particular emphasis on decoupled work and asynchronous communication, hence keeping robots productive even after human team members have left. Aside from product variety and error handling, advances towards multi-human-multi-robot teams with decentralized coordination capacities are planned.

Benchmarking: Reproducible benchmarks are required for comparable human-robot interaction research. User studies are well established in the field. However, this evaluation method does not scale well to flexible teaming. A comprehensive evaluation of flexible cobots would require extensive numbers of subjects to capture different scenarios. This issue can be overcome by observing dynamic interactions in simulation. To this end, we are working on an approach based on crowd-sourced training data to reproduce indeterministic, yet plausible human behaviour in virtual commissioning.

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Towards Active Visual SLAM

Elia Bonetto[*,†], Ph.D. Student, and Aamir Ahmad[†,*], Supervisor

Abstract— **In this work, we aim to develop an active visual SLAM approach for ground robots. The goal is to generate control commands that allow such a robot to simultaneously localize itself and map an unknown environment while maximizing the amount of information gained and consume as low energy as possible. The robot must be able to do so without any human intervention, in dynamic environments, while exploiting all the available information.**

Preferred type of presentation: Oral

Keywords: Active SLAM, Dynamic environments, Robot interaction

I. Motivation and Problem Definition

Mobile robots that assist humans in everyday tasks are increasingly popular. Self-localization and environment mapping are the key functionalities of such robots, which enable robustness in higher-level task performance. Most often, these robots operate in a previously unknown environment, e.g., in a person's house, or need to update their knowledge about it. However, many SLAM methods are still passive processes, e.g. [1], in which the robots are required to follow external control inputs and require a static world. Active SLAM, on the other hand, refers to those methods in which a robot makes 'on-the-fly' decisions regarding its own movements. However, those methods focus mainly on the exploration phase and do not address changing worlds. Integrating the dynamic part of the world is essential to have a fully autonomous robot that can update its knowledge and work without supervision at any given time. Moreover, this is also necessary to enable full interaction capabilities.

II. Related Work

A. Active SLAM

Most active SLAM algorithms consist of the following workflow [2] – i) selection of candidate goals, ii) path generation for those goals, iii) computation of path utilities, and, iv) execution. The goals, most of the time, consist of points that lie at the boundary between explored and unexplored space (frontier points). Other approaches, like NBV and RH techniques, use only a short-term horizon but continuously change their objective and, without careful tuning, might get stuck in local minima. Therefore, the combination with RRT/graph planners arose as a solution, especially for drones and outdoor exploration. However, those rarely reflect changes that happen following a loop closure or relocalization event.

B. Dynamic Environments

SLAM frameworks that directly address dynamic scenes are getting more and more attention, especially for autonomous navigation systems. The most common approach is to process the visual data and remove the dynamic obstacle so that the system is not affected by it. This already shows some promising results both in the reliability of the system and on the quality of the reconstructed environment.

III. Own Approach and Contribution

Our active V-SLAM framework merges the benefits of various techniques. We use a long-term planning horizon based on frontier detection. Then, for each generated path, we select the best orientation at every waypoint based on our utility function. After selecting the best goal based on a weighted-average utility we start the movement. However, we do not just blindly execute it. Indeed, every time a waypoint is reached we re-compute the following optimized orientation based on the recently gathered information. Finally, features are of utmost importance in such a system. Therefore, we balance our control considering both the desired orientation and a local feature-following scheme. Those three layers allow us to combine long-term planning (toward frontiers), NBV (waypoint optimization), and RH techniques (re-computation of the optimal heading). Preliminary results on this are available on ArXiv [3] with open sourced code. However, we want to deploy this system also in dynamic environments. Capturing and discerning the static and the dynamic part of a scene for a real-world deployment is of critical importance both in terms of performance and privacy. Being robust to occlusions and false clues, especially during localization, is essential to have a reliable system. With these capabilities, it would be possible to employ our robot in any given environment, without supervision, and build reliable maps even in crowded situations.

[*]Max Planck Institute for Intelligent Systems, Tübingen, Germany. firstname.lastname@tuebingen.mpg.de

[†]Institute for Flight Mechanics and Controls, The Faculty of Aerospace Engineering and Geodesy, University of Stuttgart, Stuttgart, Germany. firstname.lastname@ifr.uni-stuttgart.de

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Smart Interaction System for Autonomous Bus in Pedestrian Zone

Qazi Hamza Jan[1] and Karsten Berns[2]

Abstract— **For driver-less vehicles to drive in pedestrian zones, it is important to build trust between the vehicle and pedestrians. To avoid any contretemps between the vehicle and pedestrian, a clear intent of the vehicle should be delivered. This paper presents an interaction system for an autonomous bus in pedestrian zones based on the recognized activity of the pedestrian. It uses behavior-based model to compete for priority between bus commands and pedestrian commands.**

Preferred type of presentation: Oral

I. Motivation and Problem Definition

With the advancement in Autonomous Vehicle(AV) technology, the focus has also shifted to Autonomous buses in Pedestrian zones. These buses are smaller in size than the traditional buses on the road and can carry around 10 passengers. They are mainly used for first and last-mile travel. Driving autonomously in a pedestrian zone is a challenging task due to the unstructured environment and pedestrians. A great deal of care has to be taken while driving in a pedestrian zone. A huge number of pedestrians are inhering in pedestrian zones. Pedestrians exhibit various behaviors towards other pedestrians and vehicles. Sometimes, these behaviors are random and risky.

AVs for pedestrian zones are equipped with special scanners to detect any kind of obstacles in the nearby driving area. Algorithms are configured in such a way to permanently halt based on the velocity and stopping distance of the vehicle. People take advantage of such behavior in the vehicle, and the vehicle encounters a freezing state. In this state, the vehicle always stops due to pedestrians, regardless of its higher priority. Repeatedly stopping of autonomous shuttles becomes vexing for passengers inside the bus. Passengers expect to have a smooth and timely trip on the bus as compared to walking the same route. In conventional vehicles, the driver communicates for priority. Hence, a pragmatic approach to solving such a problem is to interact with the pedestrians and clarify priority between the vehicle and the pedestrians. Consequently, trust is developed between the vehicle and the pedestrian. By opportune use of different interaction commands, confusion can be avoided.

II. Related Work

This work is an extention of [1]. Pedestrian Interaction System(PIS) was integrated with navigation algorithm to test the effects of interaction in crowded pedestrian a simulated environment. It was observed, with PIS enabled, the vehicle took less time. Authors in [2] use Intent Communication System(ICS) to convey useful information to the pedestrians. The ICS was test with real vehicle as well.

Fig. 1. Driver-less bus at Technical Universität Kaiserslautern.

III. Own Approach and Contribution

Figure. 1 shows a bus model we are using in the campus of Technische Universtät Kaiserslautern. Other than the conventional sensors for AVs, it has an LED display and sound system. Both visual and audio aids are used for interaction. For intelligent interaction, pedestrian skeletons are detected using a stereo camera. Based on different 3D joint locations, angles are calculated. These angles are then fused from different body parts to anticipate different postures of the pedestrians. Interaction commands are then generated based on the recognized posture of the pedestrian. Here, it is important to prioritize information generated from the bus itself, such as door opening/closing, driving, etc. The system is design using Behavior-Based Control Architecture(iB2C) [3]. The coordination among different modules is decided by the active behavior. In our case, vehicle commands always inhibits the Pedestrian interaction commands.

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[1]Qazi Hamza Jan is a PhD student in Robotic Research Lab, Department of Computer Science at Technische Universtät Kaiserslautern, Germany hamza@cs.uni-kl.de

[2]Karsten Bern is a professor in Department of Computer Science, Techniche Universität Kaiserslautern, Germany. berns@cs.uni-kl.de

On the Principle of Transference and its Impact on Robotic Innovation

Bertold Bongardt[1]

Abstract— **This document describes the concept for a presentation at the DGR Days 2021. The talk shall use the principle of transference as the major guidance to describe historical and recent developments in computational kinematics and to outline their relevance for research and innovation in robotics.**

Preferred type of presentation: Oral

I. Motivation and Problem Definition

The engineering of novel, technical solutions is depending on the progress in the exact sciences. For the mechanical domain of a robotic system, it has been observed that "the kinematics of a mechanical device are defined mathematically" and that "the requirement that the kinematics can be efficiently computed adds constraint, that ultimately affects mechanical design." [1]. The other way around, this observation motivates to ask: Which mathematical problems in robot kinematics and dynamics can be computed efficiently? And where is the boundary located that separates the problems with known tractable solutions from those without? If these questions are answered more thoroughly, efficient innovations in the scope of the mechanical synthesis of robotic systems can be estimated.

II. Related Work

The principle of transference has been formulated by Alexander Petrovich Kotelnikov and Eduard Study more than hundred years ago. The principle claims that "algebraic identities of ordinary trigonometry hold true for dual angles" in coherence with [2]. With respect to the geometry of space, "the principle of transference says that expressions concerning systems of position vectors remain true for systems of lines if the vectors are replaced by the corresponding dual vectors." [3]. From the author's point of view, the potential of the principle of transference has not been fully employed as of today: in first regard, for computational purposes in theoretical mechanics and, in second regard, for the development of innovative applications in robotics.

III. Own Approach and Contribution

In order to justify this assumption, the future talk shall outline findings which have been obtained by applying the principle of transference in kinematic analysis. In particular, it is foreseen (a) to outline the system of dual numbers [4] in analogy with the system of complex numbers from a geometric-kinematic point of view; (b) to characterize the adjoint (6×6)-matrix as the 'real-number pendant' of (3×3)-matrices with dual-number entries [5], [6]; (c) to motivate the parametrization by Sheth and Uicker of general mechanisms as dual-number pendant of well-known Euler angles [7]; (d) to reflect the basic geometric operations 'projection', 'rejection', and 'orthogonalization' for the geometry of linear 3-vectors and their transferred concepts for the geometry of oriented lines [8]; (e) to review the geometric problems and solution methods by Paden and Kahan and their generalized instances for line geometry [9], [10]; and (f) to consider the line-geometric approach which yields a unified singularity analysis of general spatial kinematic chains [11]. Further potential of the principle of transference for the advancement and education in mechanism science and for the design of future robotic systems shall be indicated in conclusion.

[1]Bertold Bongardt is working as a lecturer at the Institut für Robotik und Prozessinformatik (IRP), Technische Universität Braunschweig, 38106 Braunschweig, Germany b.bongardt@tu-bs.de

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Sustainable Production enabled by remanufacturing

Jan-Philipp Kaiser[1], Constantin Hofmann[1], Niclas Eschner[1]

***Abstract*— The growth of humanity, the scarcity of ressources and significant climatic changes require an adaption of the economic behavior. Moving from a linear economy which is focussing on producing new products to a circular econonomy which uses remanufacturing processes to reintroduce already used products or components as part of new products to the market can make a decisive contribution to increase sustainability. However, the assessment of products returning from a life-cylce is still a manual undertaking requiring highly-skilled and experienced workers. This contribution reports on a concept of how autonomeous inspection can help to reduce the manual effort and increase quality.**

Preferred typ of presentation: Oral

I. Motivation and Problem Definition

The current social, economic and global political situation is characterized by great uncertainty. The periods of time in which humanity is undergoing profound changes are becoming increasingly short-cyclic. In view of the growing population worldwide and the increasing scarcity of central raw materials, changes have to be made today in order to look into a sustainable future [1]. This is especially true for manufacturing companies, as the traditional linear economic approach "take – make – use – dispose" is no longer a recipe for success in the long run. Closed-loop models such as remanufacturing offer the opportunity to continue to operate economically but also ecologically.

II. Related Work

In remanufacturing, used products are recovered, dismantled and selected components are returned to the production process [2]. In particular, the decision as to whether an used product is suitable for a further life cycle is nowadays mainly made by skilled personnel following an inspection, since the use of the products results in a high variance in the states of the declining old products [3]. In addition to possibly missing product components, signs of aging and wear and tear such as corrosion or cracks must be detected and evaluated at the same time [4]. This poses unprecedented challenges for automated quality assurance concepts, as they have to adapt to constantly changing conditions. Figure 1 shows the remanufacturing flow and its challenges starting from the initial inspection, to the disassembly process, the following component inspection and eventually required processing steps to the final reassembly of the remanufactured product.

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[1]wbk Institute of Production Science, Karlsruhe Institute of Technologie (KIT), Karlsruhe, Germany constantin.hofmann@kit.edu

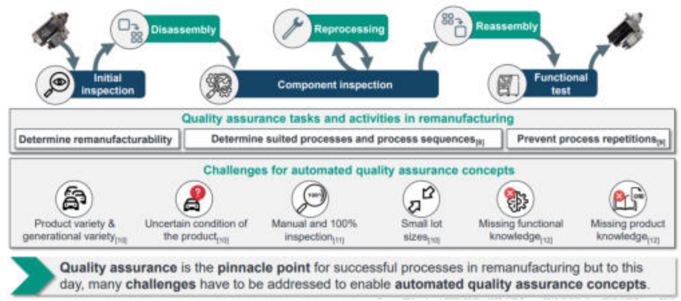

Fig. 1. Remanufacturing system and its challenges

III. Own Approach and Contribution

To improve the autonomy of the inspection process, a self-learning roboter-based system is proposed. A robot-mounted camera and a laser scanner are used to capture images of the product of unknown condition. Each image and scan is analyzed to detect surface and geometrical defects. Depending on the results, the system determines itself the next best view angle to capture the next picture. The aim is to gain autonomeously and with minimum effort information on the condition of the component to feed the information to the scheduling system to determine if and in which from the component can be used in the remanufacturing process.

To determine an initial strategy to capture the required images, human operators are obsevered. These observations are used to determine the points of interest for the quality inspection as well as the order of the inspection steps. These initial views are used as a starting point of the self-learning system.

Acknowledgment

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